Wide Band and Wide Field Imaging - II

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National Centre for Radio Astrophysics / TIFR
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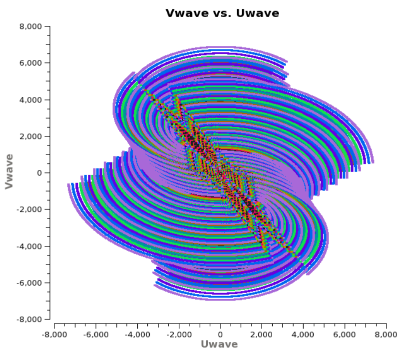
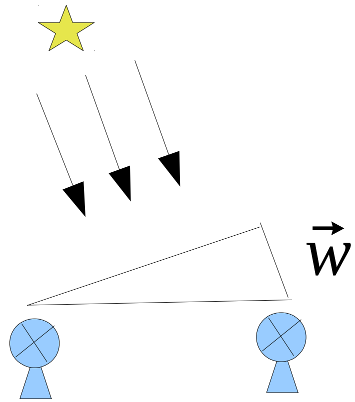
Lecture 1

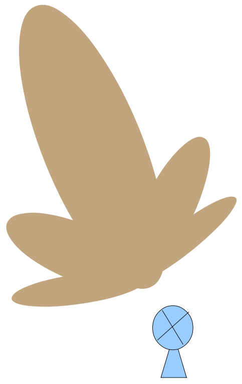
Wide Band Imaging
Sky and instrument change with frequency
=> Cube vs MFS, wideband/multiscale model



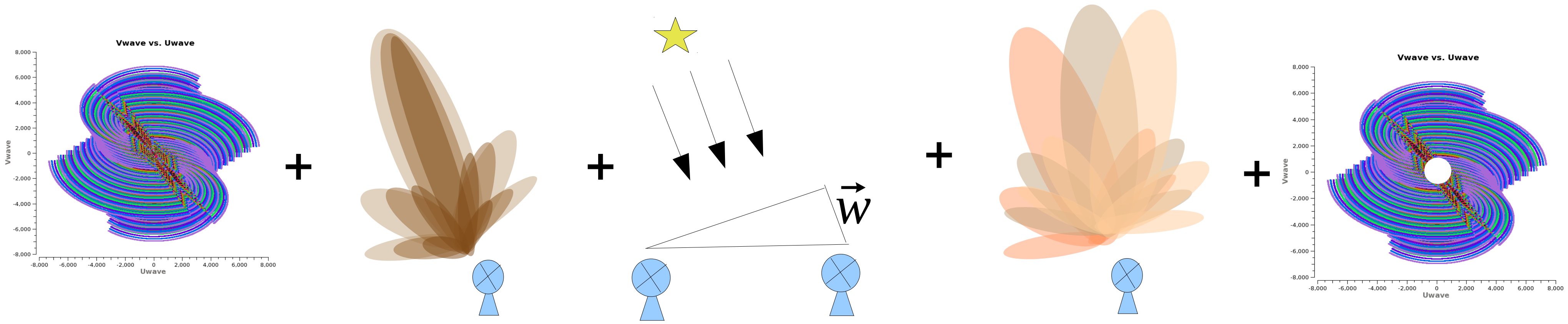
Wide Field Imaging
non-coplanar baselines and the W-term
=> W-Projection, W-Stacking, Faceting, 3D FFTs



Full Beam Imaging
antenna primary beams
=> pbcor, A-Projection, beam models



Lecture 2



Wide-Band + Primary-Beams + W-term + Mosaic + Single-Dish

=> Primary Beams change with frequency
=> Combine multiple pointings together in the same image
=> Fill gaps in uv-coverage with single dish data

Imaging Framework
=> How is this done in software packages that you will use ?

Measurement Equation

The visibility measured by each baseline *ij* at one frequency and time

$$V_{ij}^{obs}(\nu,t) = M_{ij}(\nu,t) S_{ij}(\nu,t) \iiint M_{ij}^{s}(l,m,\nu,t) I(l,m,\nu,t) e^{2\pi i (ul+vm+w(n-1))} dl\, dm\, dn$$

Direction Independent Gains

- Eliminated during calibration

Primary Beams

- Power pattern varies with time, frequency and baseline

– PBcor (post-deconvolution)
– A-Projection
- WB-A-Projection
- Mosaics

Full Beam

Sky-brightness varies with frequency (time)

- All sources have spectral structure (some vary with time)

– Cube Imaging
– Multi-Frequency Synthesis (MFS)
– Multi-Term-MFS
(point source or multi-scale models)

Wide-Band

W-Term

-Non-coplanar baselines

-Sky curvature

– Faceting
- W-Projection
- 3D FT
- W-Stacking

Wide-Field

Wide Band + Full Beam/Wide-field

+ Mosaics

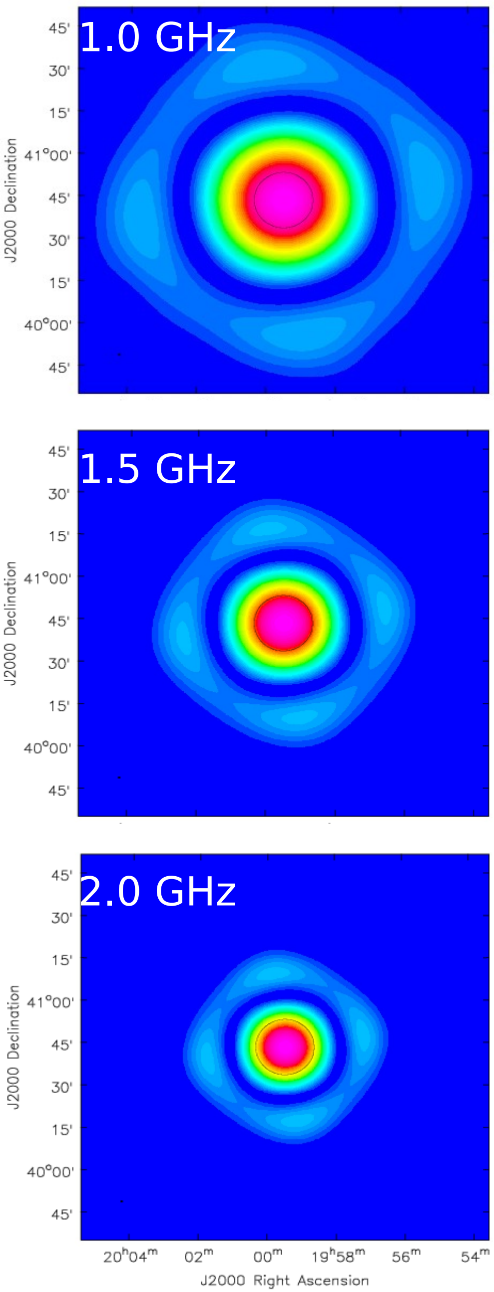
+ Single Dish

Example : Imaging the G55 supernova remnant

Imaging Framework

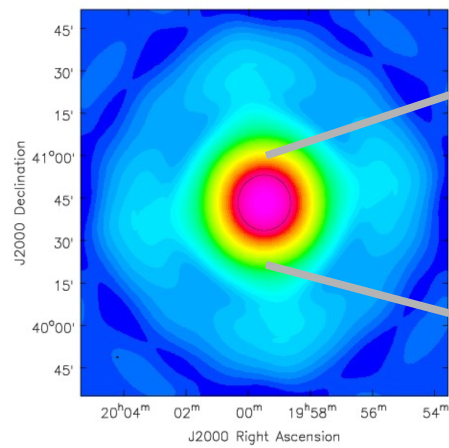
Wide-Band Wide-Field Imaging : Primary Beams

VLA PBs

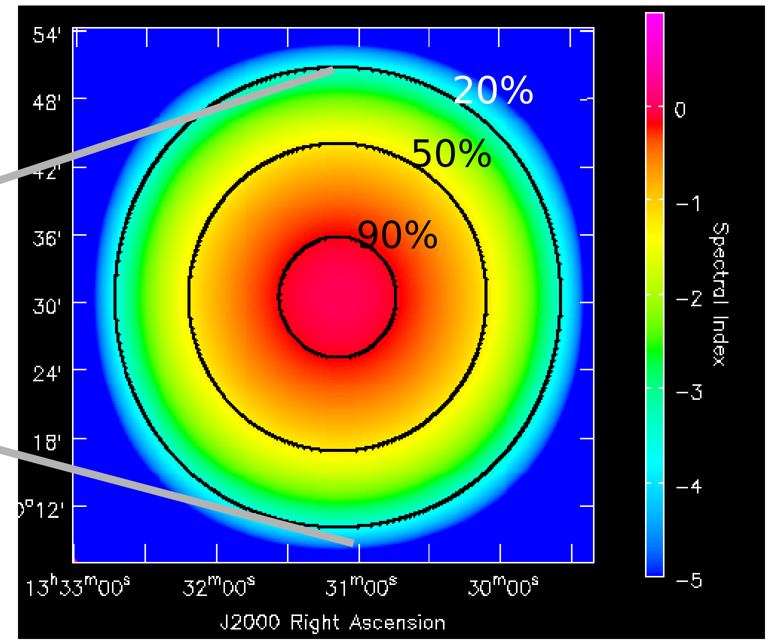


- Primary beam scales (or changes) with frequency
- MFS combines data across frequency

Average Primary Beam



Spectral Index of PB

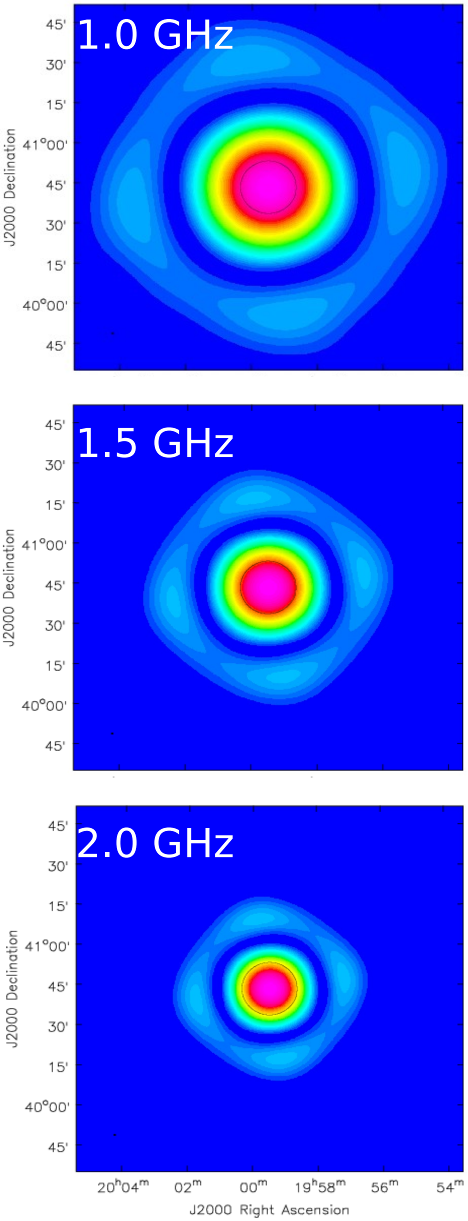


A very wide shelf of sensitivity outside the main lobe

For VLA L-Band (1-2 GHz)
- About -1.4 at the HPBW
  (15 arcmin from the center)

$$I^{obs}_{wf,wb} = \sum_{\nu} \left[\left(P_{\nu} \cdot I^{sky}_{\nu} \right) * PSF_{\nu} \right]$$

Wide-Band Primary Beam Correction



Cube Imaging

-- Sky model represents $I(\nu)P(\nu)$
-- Divide the output image at each frequency by $P(\nu)$

Multi-Term MFS + Wideband-PBcor

-- Taylor coefficients represent $I(\nu)P(\nu)$

-- Polynomial division by PB Taylor coefficients

$$\frac{(I^m_{0,} I^m_{1,} I^m_{2,} \ldots)}{(P_{0,} P_{1,} P_{2,} \ldots)} = (I^{sky}_{0,} I^{sky}_{1,} I^{sky}_{2} \ldots)$$

Wideband A-Projection

-- Remove $P(\nu)$ during gridding (before model fitting)

$$A_\nu^{-1} \approx \frac{A^T_{\nu_c}}{A^T_{\nu_c} * A_\nu} \quad \text{where} \quad P_\nu \,.\, P_{\nu_c} \approx P^2_{\nu_{mid}}$$

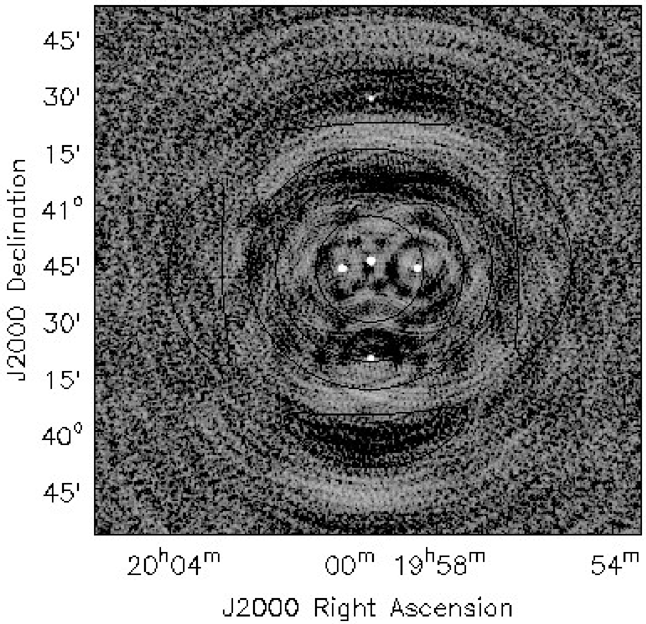
-- Output spectral index image represents only the sky

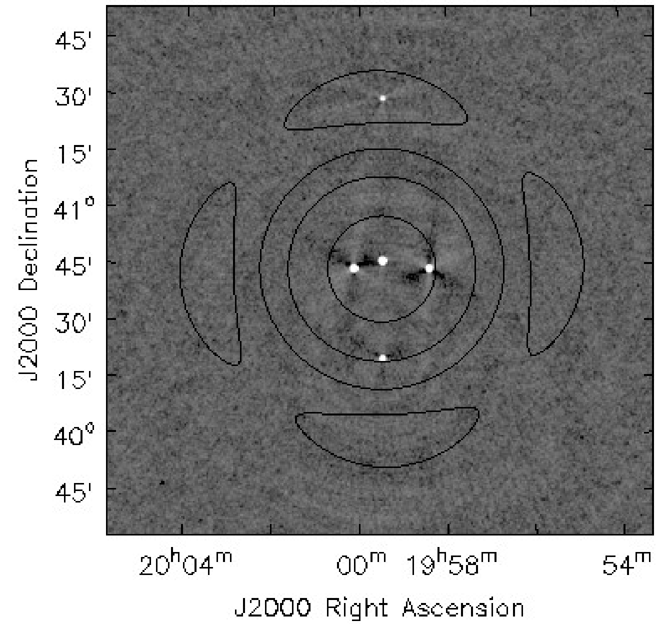
Bhatnagar et al, 2013

Wide Band Full Beam imaging – Different algorithms

Basic MFS imaging

(no WB,WF corrections)



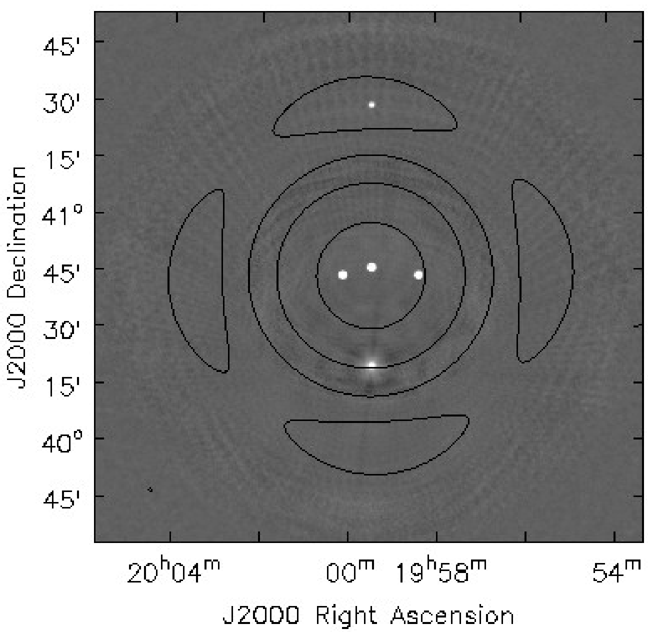


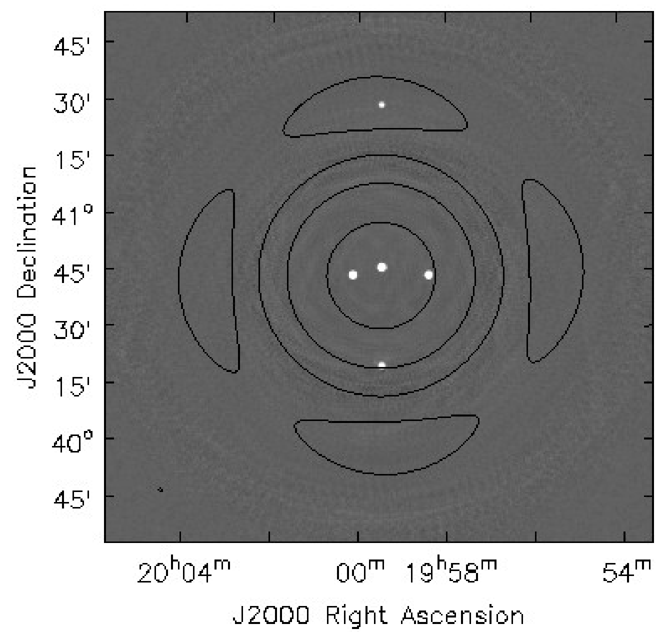
MT-MFS wideband imaging

(No WF corrections, PB freq dependence part of sky model)

MT-MFS wideband imaging + A-Proj

(PB^2 freq dependence part of sky model)



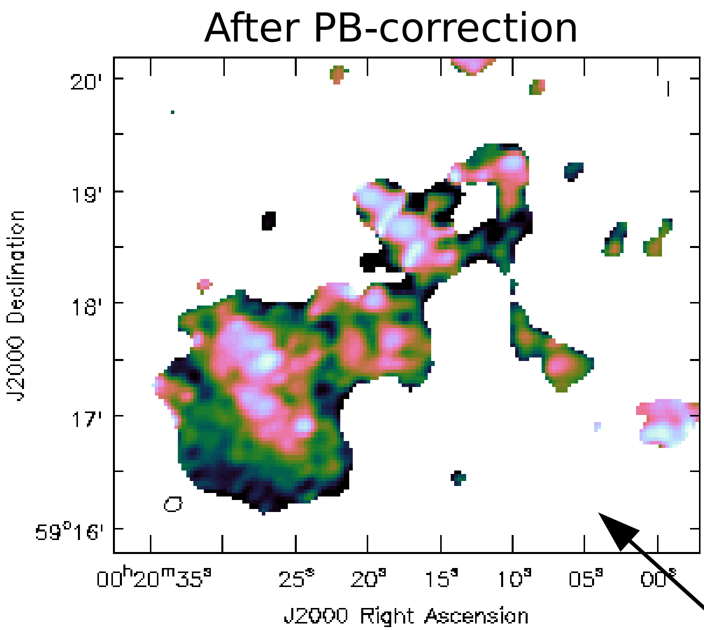


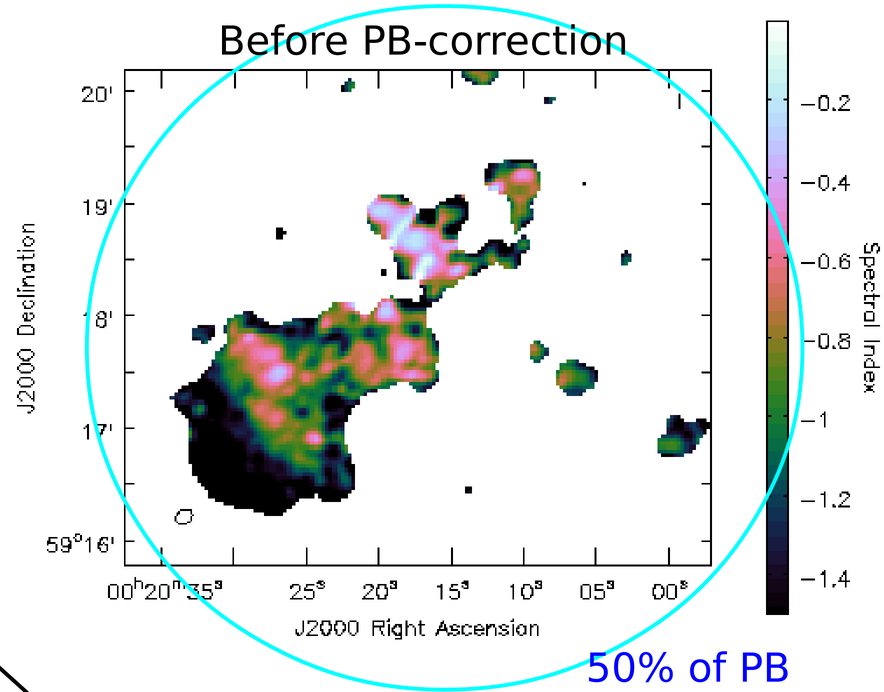
MT-MFS wideband imaging + WB-A-Proj

(PB freq dependence removed during gridding)

Spectral Index : IC10 Dwarf Galaxy

[Heesen et al, 2011]

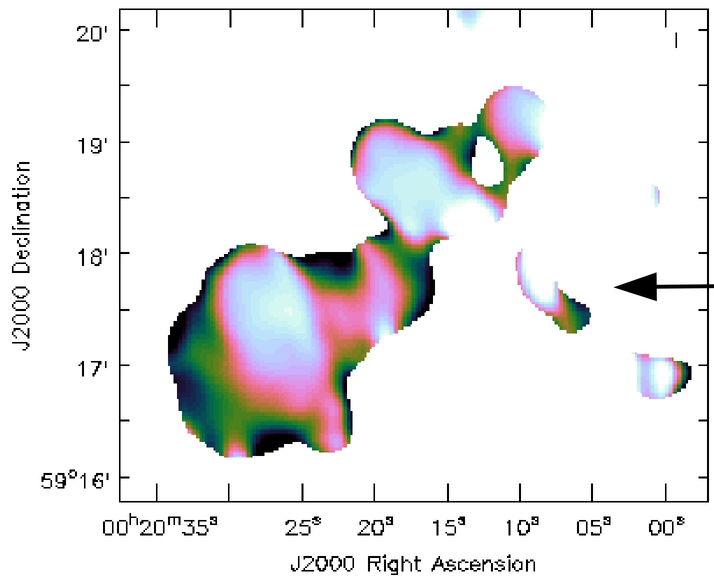




IC10 Dwarf Galaxy :

Spectral Index across C-Band.

Dynamic-range ~ 2000



MT-MFS : Wide-band PB-correction after multi-term multi-scale MFS.

Cube : Spectral-index map made by cube imaging, smoothing to lowest resolution, and spectral fitting.

Wide Band + Full Beam/Wide-field

+ Mosaics

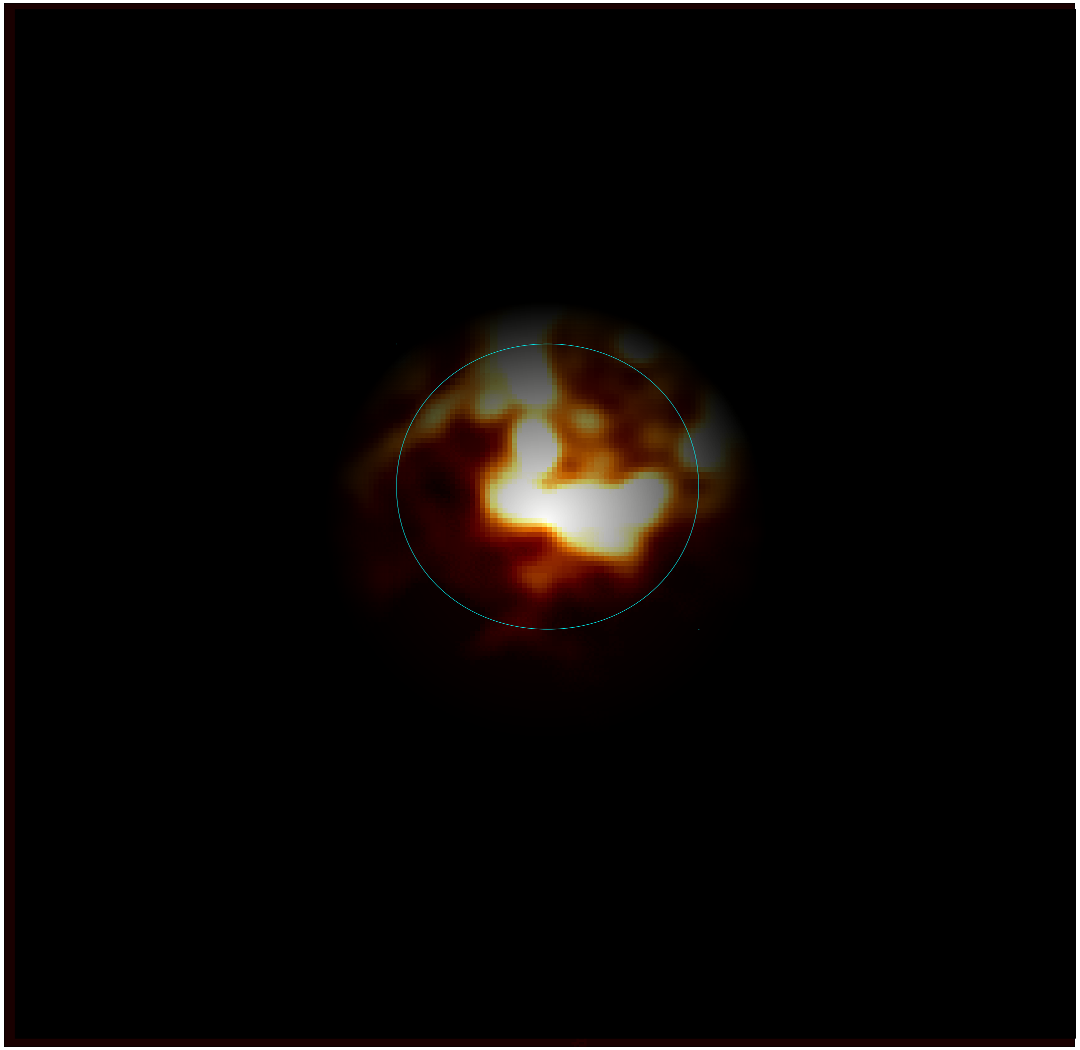
+ Single Dish

Example : Imaging the G55 supernova remnant

Imaging Framework

Mosaics

Combine data from multiple pointings to form one large image.



Combine pointings either before or after deconvolution.

Stitched mosaic :

-- Deconvolve each pointing separately
-- Divide each image by PB
-- Combine as a weighted avg

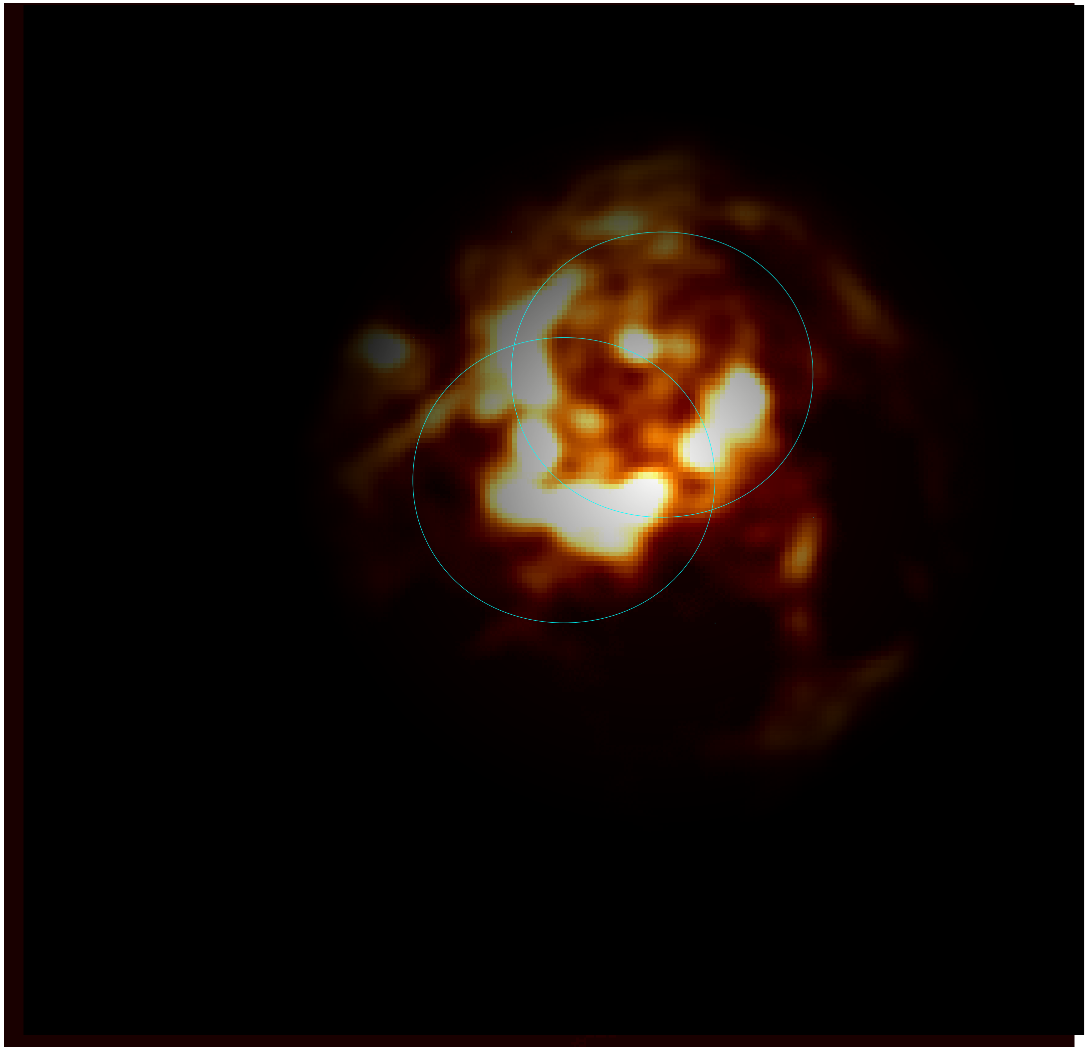
Joint mosaic :

-- Combine observed images as a weighted average
(or)
Grid all data onto one UV-grid, and then iFFT

-- Deconvolve as one large image

Mosaics

Combine data from multiple pointings to form one large image.



Two Pointings see more.....

Combine pointings either before or after deconvolution.

Stitched mosaic :

-- Deconvolve each pointing separately
-- Divide each image by PB
-- Combine as a weighted avg

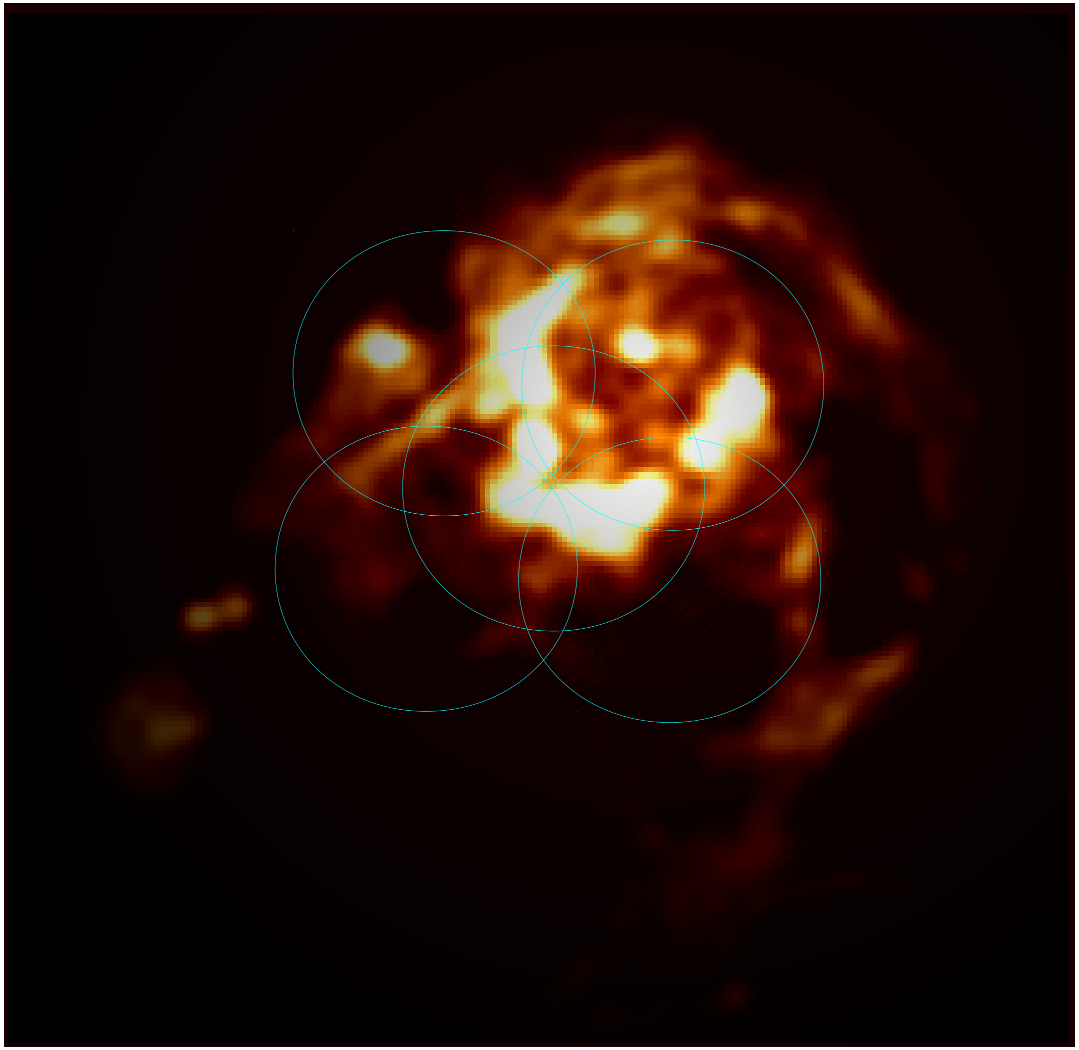
Joint mosaic :

-- Combine observed images as a weighted average
(or)
Grid all data onto one UV-grid, and then iFFT

-- Deconvolve as one large image

Mosaics

Combine data from multiple pointings to form one large image.



Use many pointings to cover the source

Combine pointings either before or after deconvolution.

Stitched mosaic :

-- Deconvolve each pointing separately
-- Divide each image by PB
-- Combine as a weighted avg

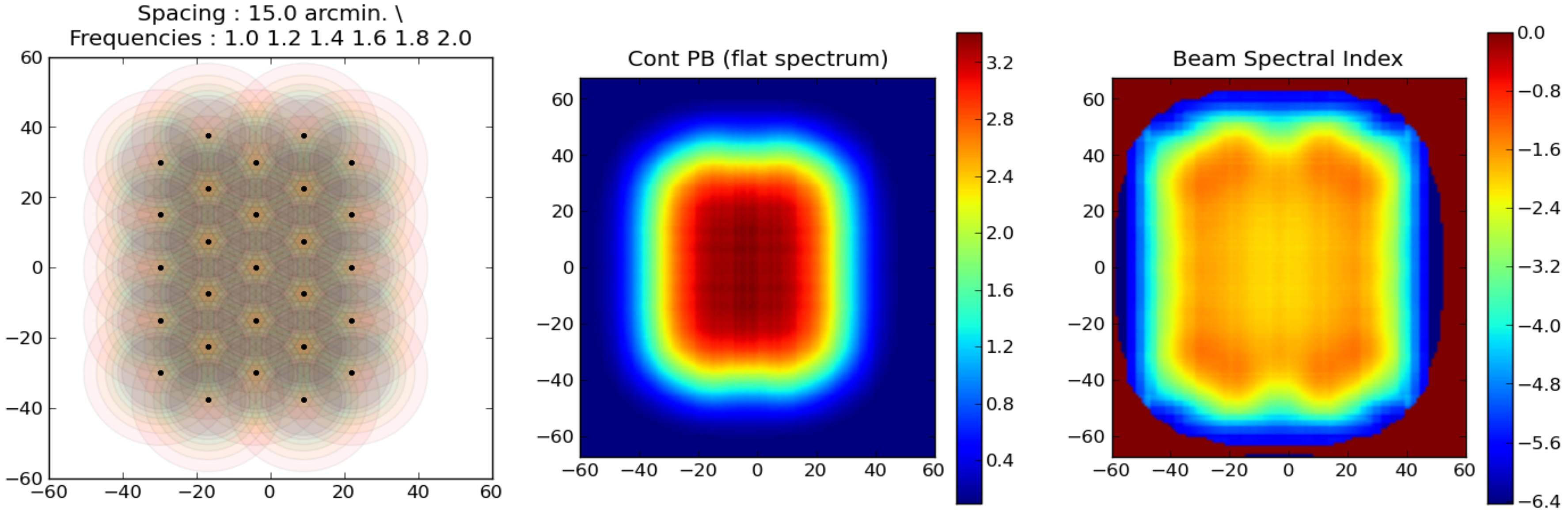
Joint mosaic :

-- Combine observed images as a weighted average
(or)
Grid all data onto one UV-grid, and then iFFT

-- Deconvolve as one large image

Wide-Band Mosaics

The mosaic primary beam has an artificial spectral index all over the FOV



Algorithms :

- Deconvolve Pointings separately or together (Stitched vs Joint Mosaic)
    - Impacts image fidelity, especially of common sources.

- Deconvolve Channels separately or together (Cube vs MFS)
    - Impacts imaging fidelity and sensitivity, dynamic range

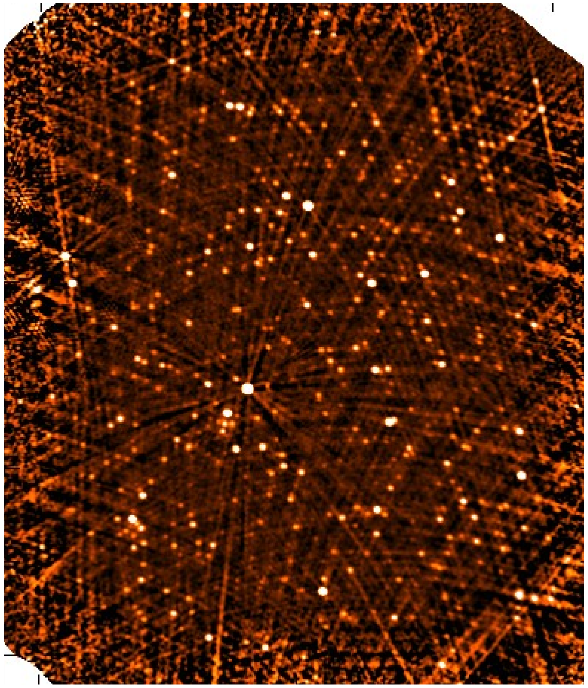
- Use A-Projection or not (Accurate vs Approximate PB correction)
    - Impacts dynamic range and spectral index accuracy

Wideband Mosaic Imaging Accuracy

[Rau et al, 2016]

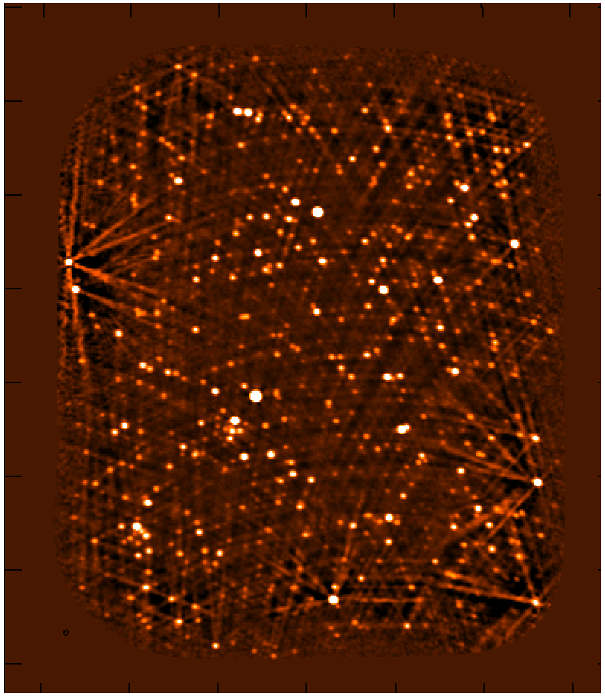
Cube + Joint Mosaic
(with static Primary Beams)

Dyn.Range = 5000:1



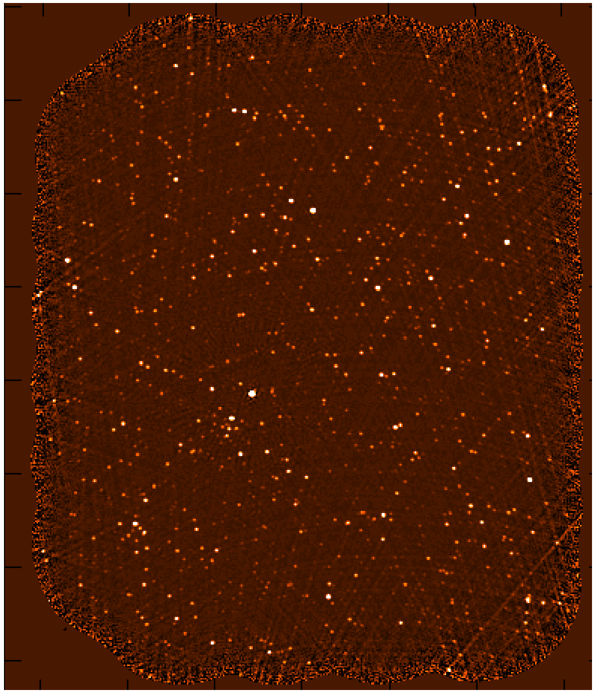
Cube + A-Projection + Joint Mosaic

Dyn.Range = 10000:1



Wideband A-Proj + Joint Mosaic + Multi-term MFS

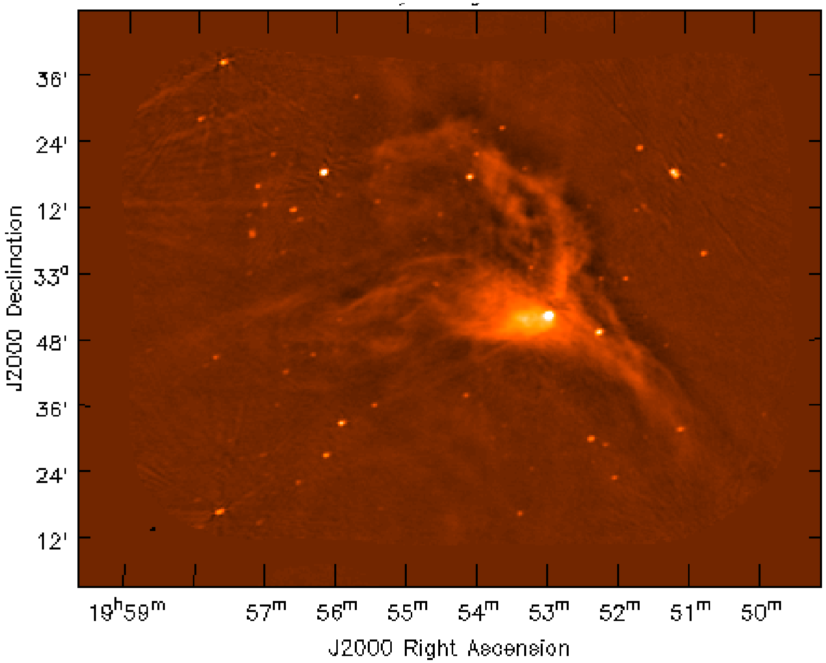
Dyn.Range = 40000:1



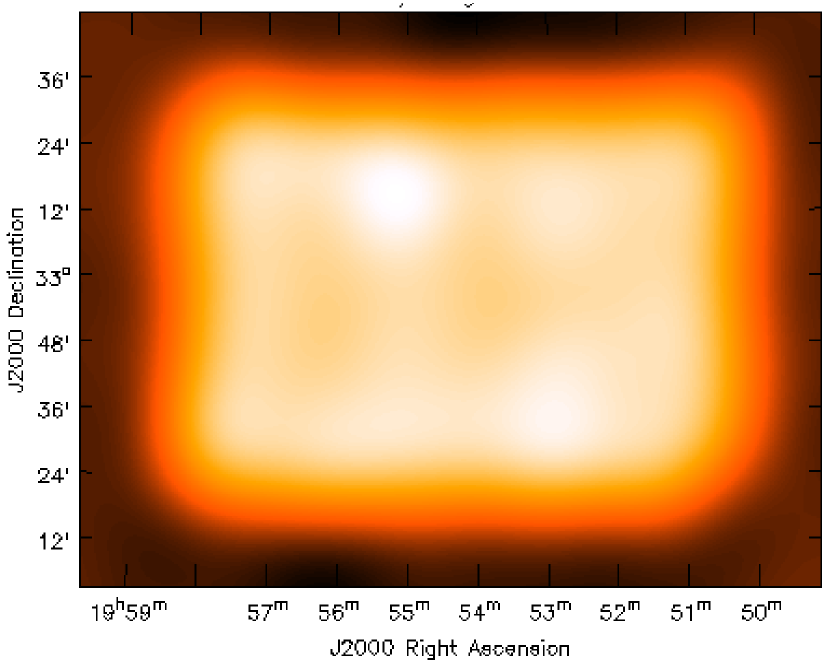
Method Intensity Range	I/I_{true} $> 20\mu Jy$	I/I_{true} $5 - 20\mu Jy$	I/I_{true} $< 5\mu Jy$	$\alpha - \alpha_{true}$ $> 50\mu Jy$	$\alpha - \alpha_{true}$ $10 - 50\mu Jy$
Cube	0.9 ± 0.1	0.9 ± 0.3	0.9 ± 0.5	-0.5 ± 0.2	-0.6 ± 0.5
Cube + AWP	1.0 ± 0.05	1.0 ± 0.2	1.0 ± 0.3	-0.15 ± 0.1	-0.1 ± 0.25
MTMFS + WB-AWP	1.0 ± 0.02	1.0 ± 0.04	1.0 ± 0.15	-0.05 ± 0.05	-0.1 ± 0.2

Wideband Mosaic of CTB80 (1-2 GHz, VLA-D config)

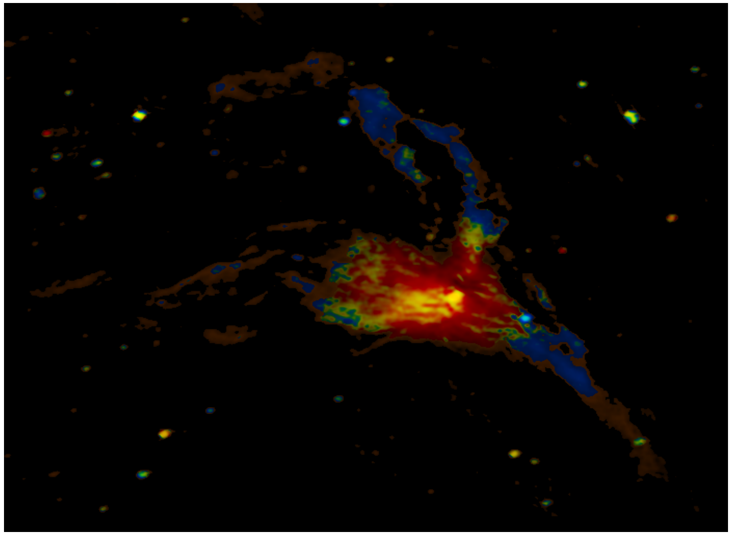
Intensity



Mosaic Primary Beam



Intensity-weighted Spectral Index



300GB calibrated dataset, 106 pointings over 1.5x2 deg, imaged with Multi-Scale Multi-Term MFS, Joint Mosaic and WB-A-Projection.

=> Mosaic primary beam spectral index of ~ -1.5 has been removed prior to the wideband sky model fitting.

Wide Band + Full Beam/Wide-field

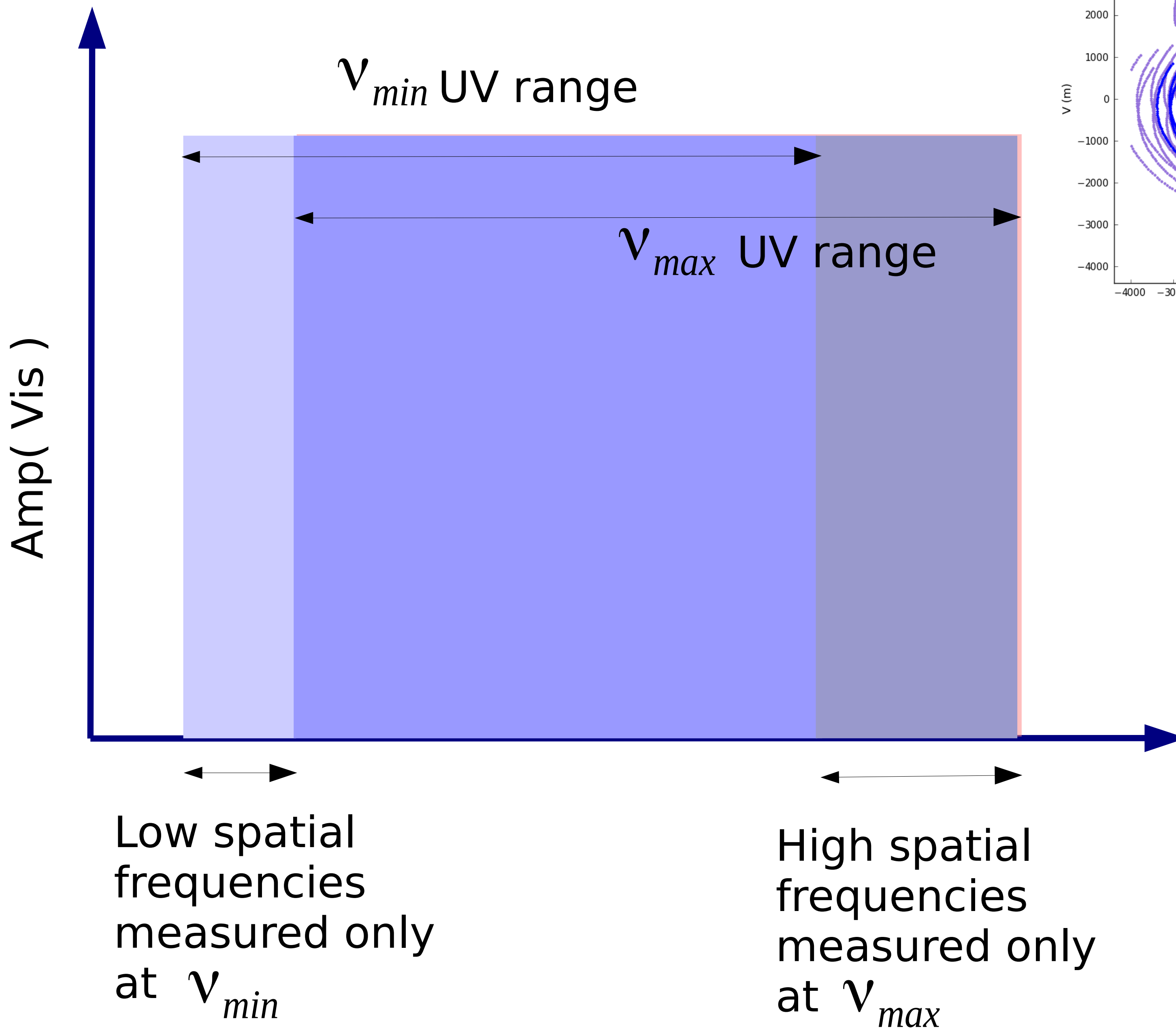
+ Mosaics

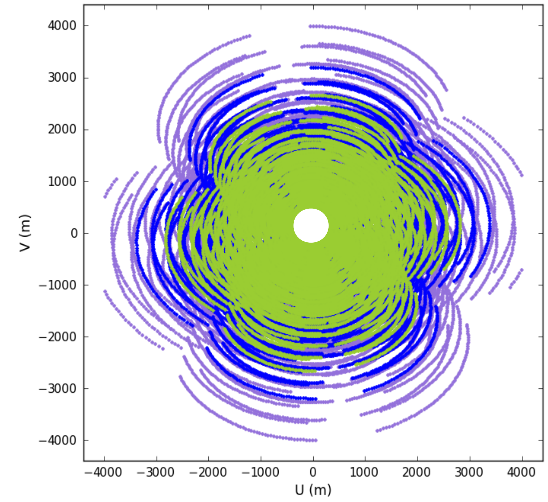
+ Single Dish

Example : Imaging the G55 supernova remnant

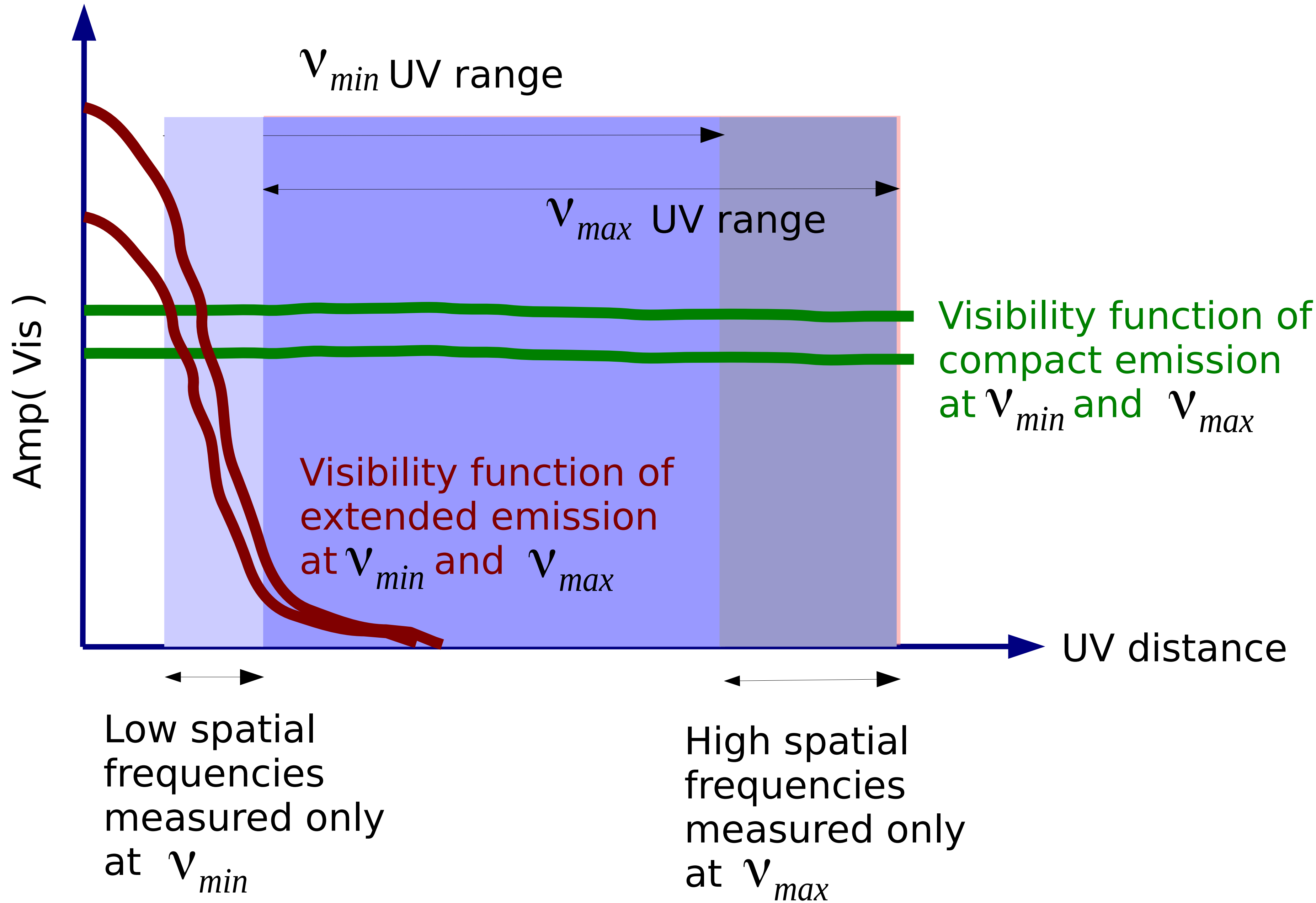
Imaging Framework

Short-spacing problem

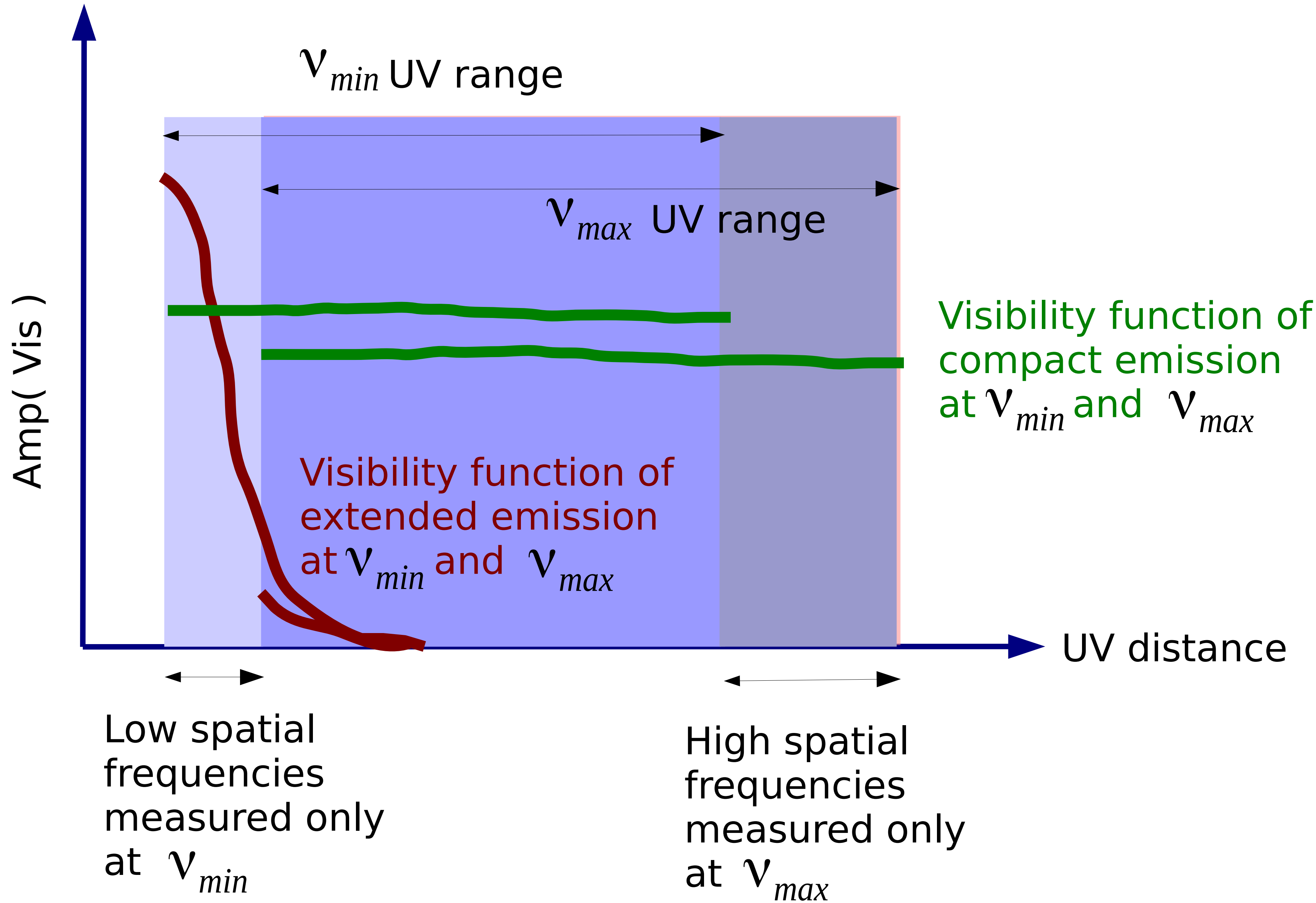




Short-spacing problem

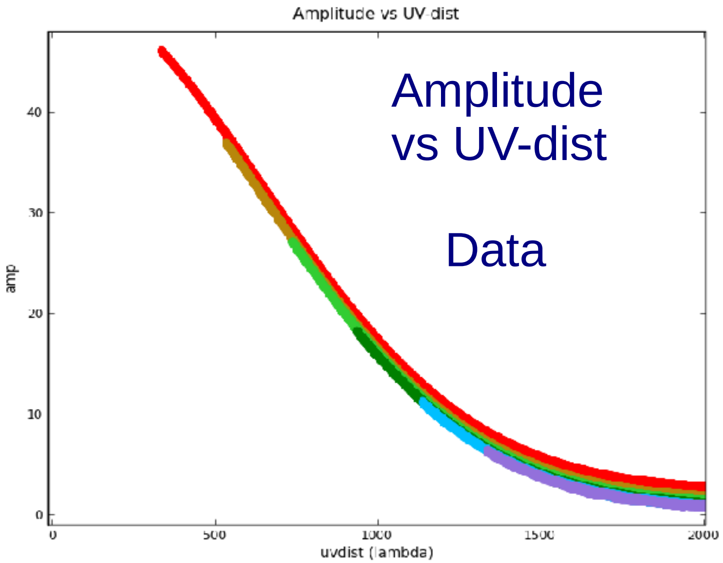


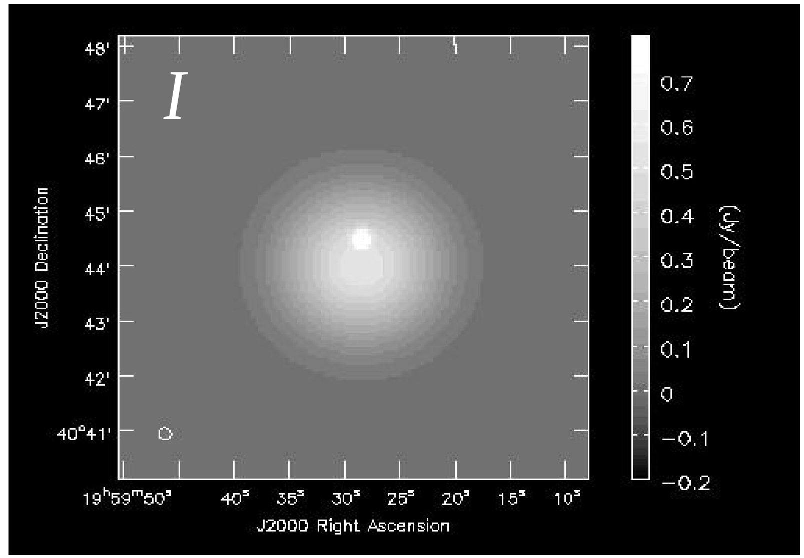
Short-spacing problem



Very large scales : Unconstrained Spectrum

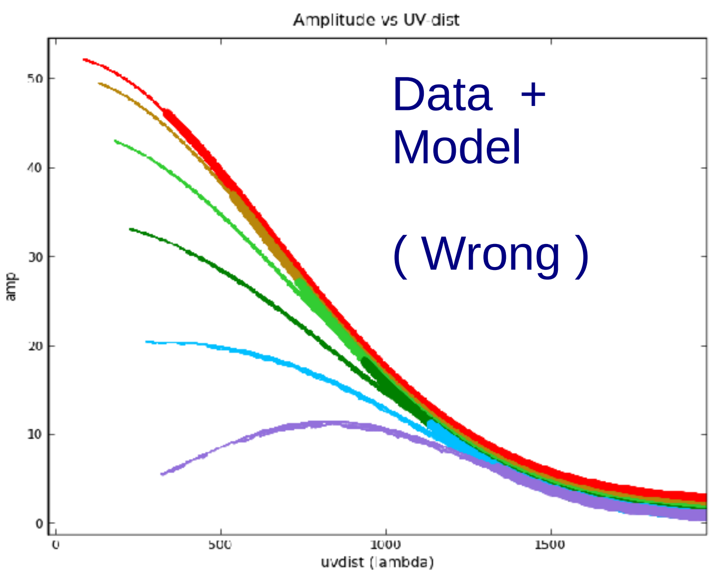
The spectrum at the largest spatial scales is NOT constrained by the data

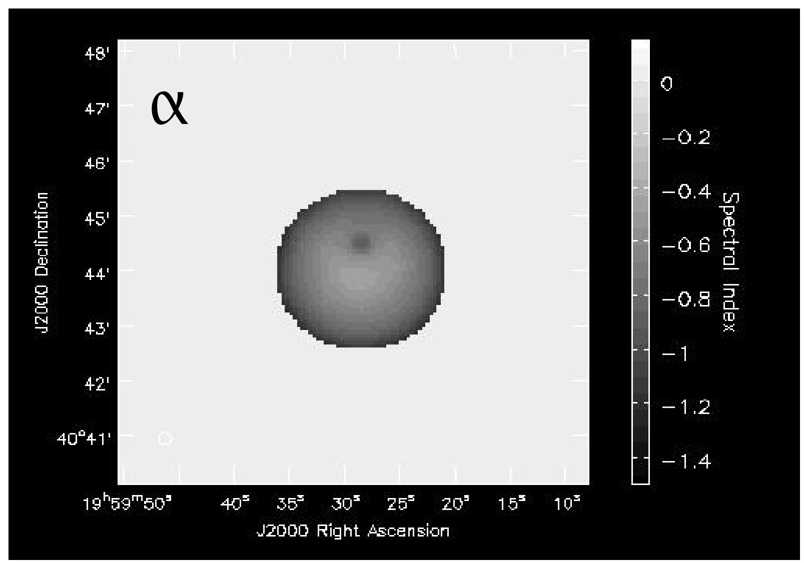




True sky has one steep spectrum point, and a flat-spectrum extended emission

Leave out shortest baselines



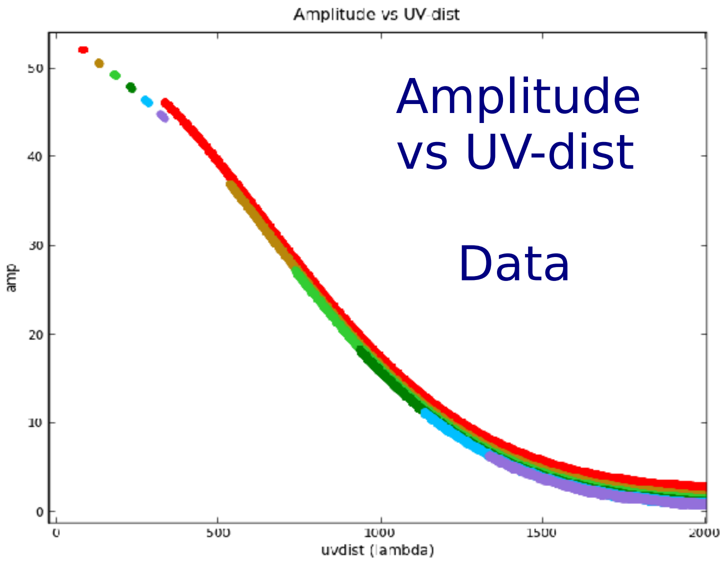


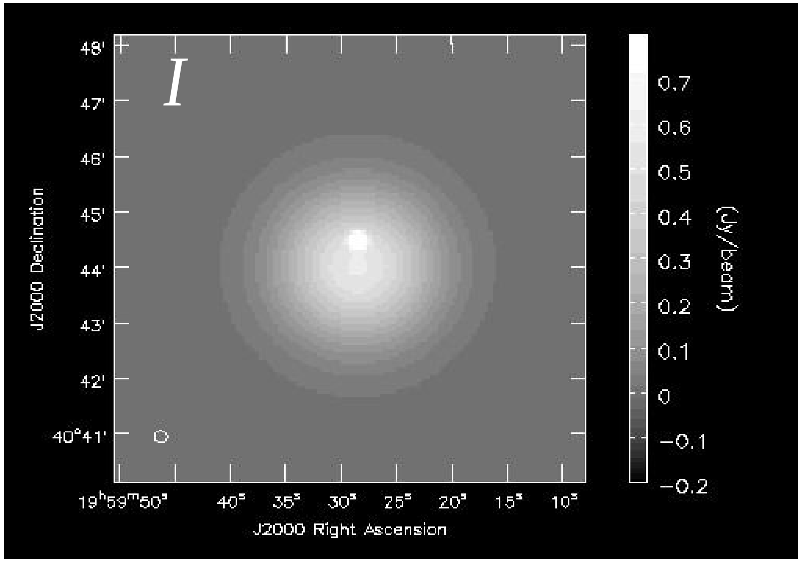
No short spacings to constrain the spectra

=> False steep spectrum reconstruction

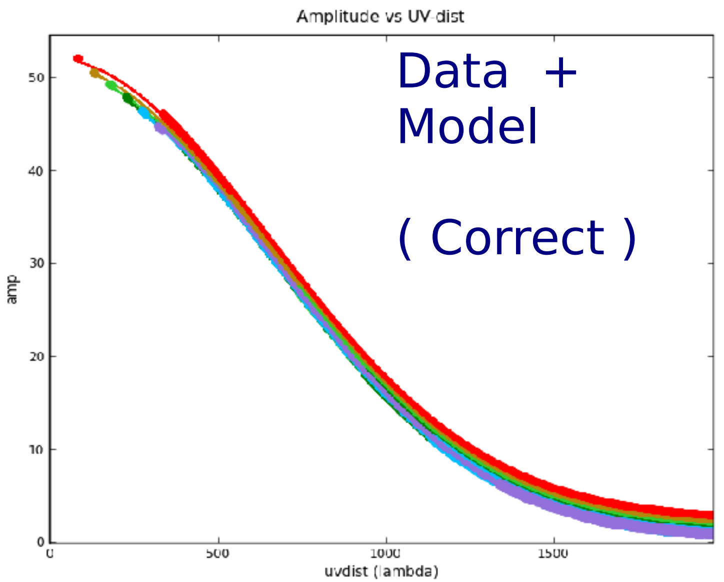
Very large scales : Need additional information

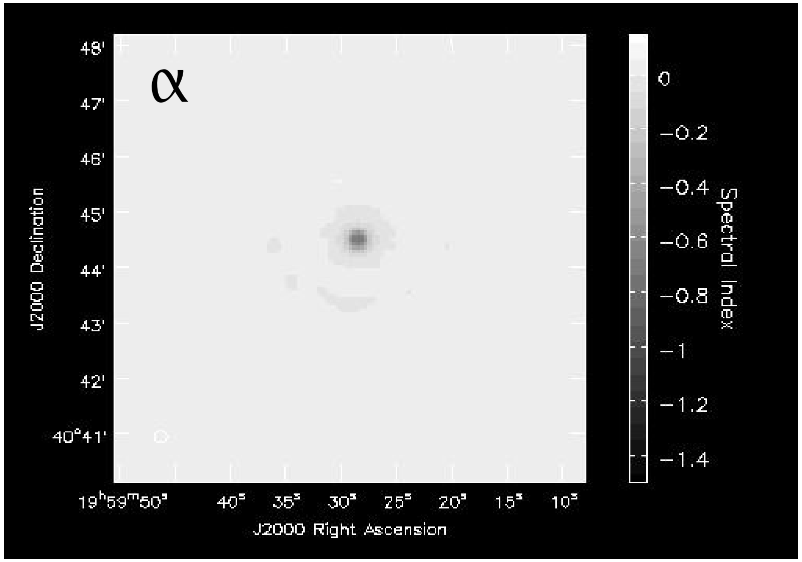
External short-spacing constraints (visibility data, or starting image model)





True sky has one steep spectrum point, and a flat-spectrum extended emission





Retain some short spacing information.

Correct reconstruction of a flat spectrum

=> So, how to add this information ?

Single Dish + Interferometer Combination

(1) Feathering : Image SD and INT data separately (in wideband mode)
Combine outputs using a UV-domain weighted average
Perform feather per Taylor coefficient map.

=> Works best when noise levels match, weighting choice is obvious, and no mid-scale artifacts in the INT-only reconstruction.

(2) Startmodel : Use SD images as a starting model for the INT reconstruction

=> Works if there is clear overlap in UV-range between SD and INT data.

(3) Artificial visibilities : Simulate virtual SD visibilities, combine with INT data

=> Flexible, a true joint reconstruction, relative weights handled externally.

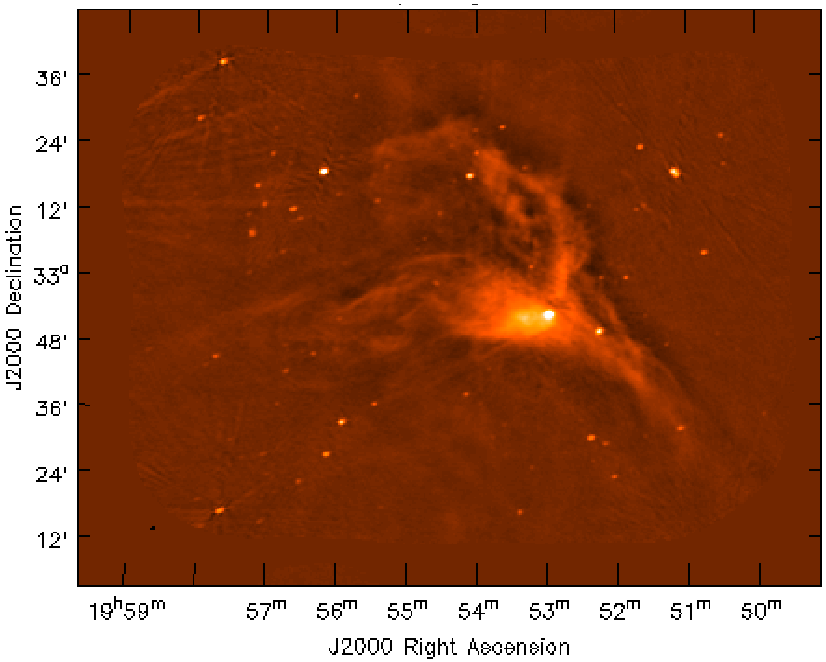
(4) Make joint residual images and PSFs before deconvolution :

=> Flexible, a true joint reconstruction, weight functions part of reconstruction framework, compatible with all wide-field, wide-band algorithms.

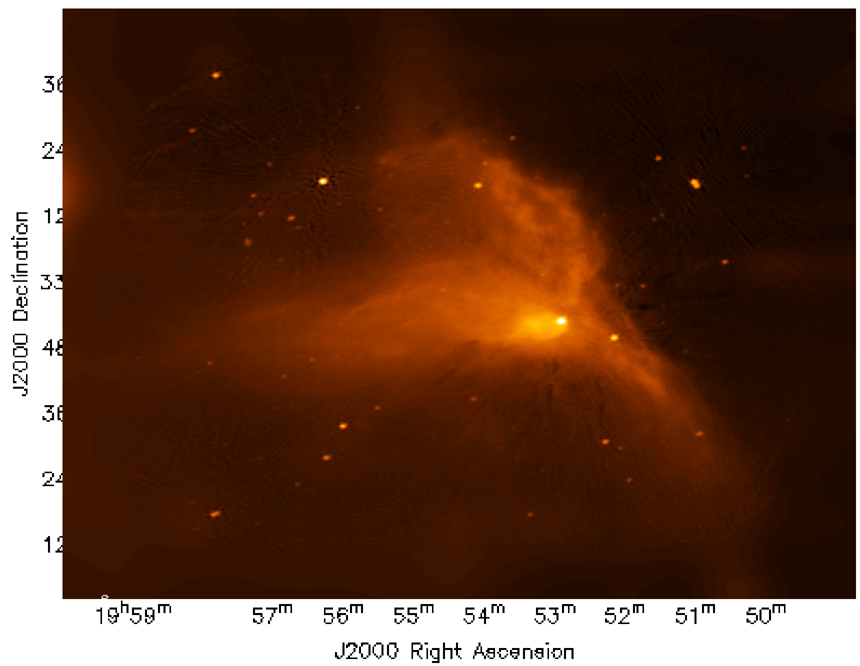
Wideband Mosaic + Single Dish data

Example : Combining Interferometer intensity image with
Single dish data at reference frequency, using Feathering.

Int WB Mosaic



Int WB Mosaic + Single Dish



Joint SD+INT Spectral Index Map => Work in progress

Algorithms needed : Multiscale, Multi-term MFS, with A-Projection, W-Projection, form a Joint Mosaic, and Joint deconvolution with wideband single dish data.

(Must run in finite time → robust parallelization)

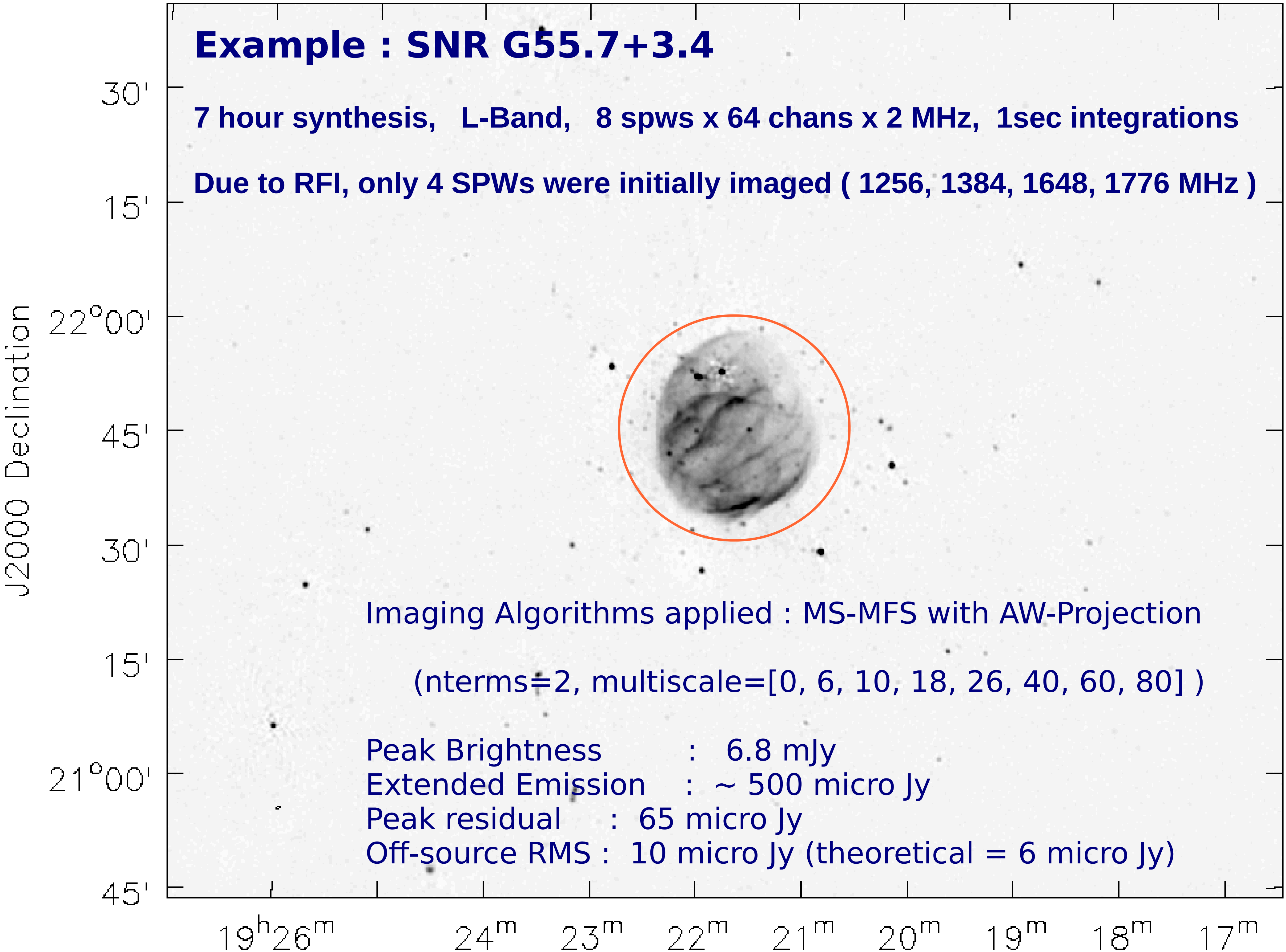
Wide Band + Full Beam/Wide-field

+ Mosaics

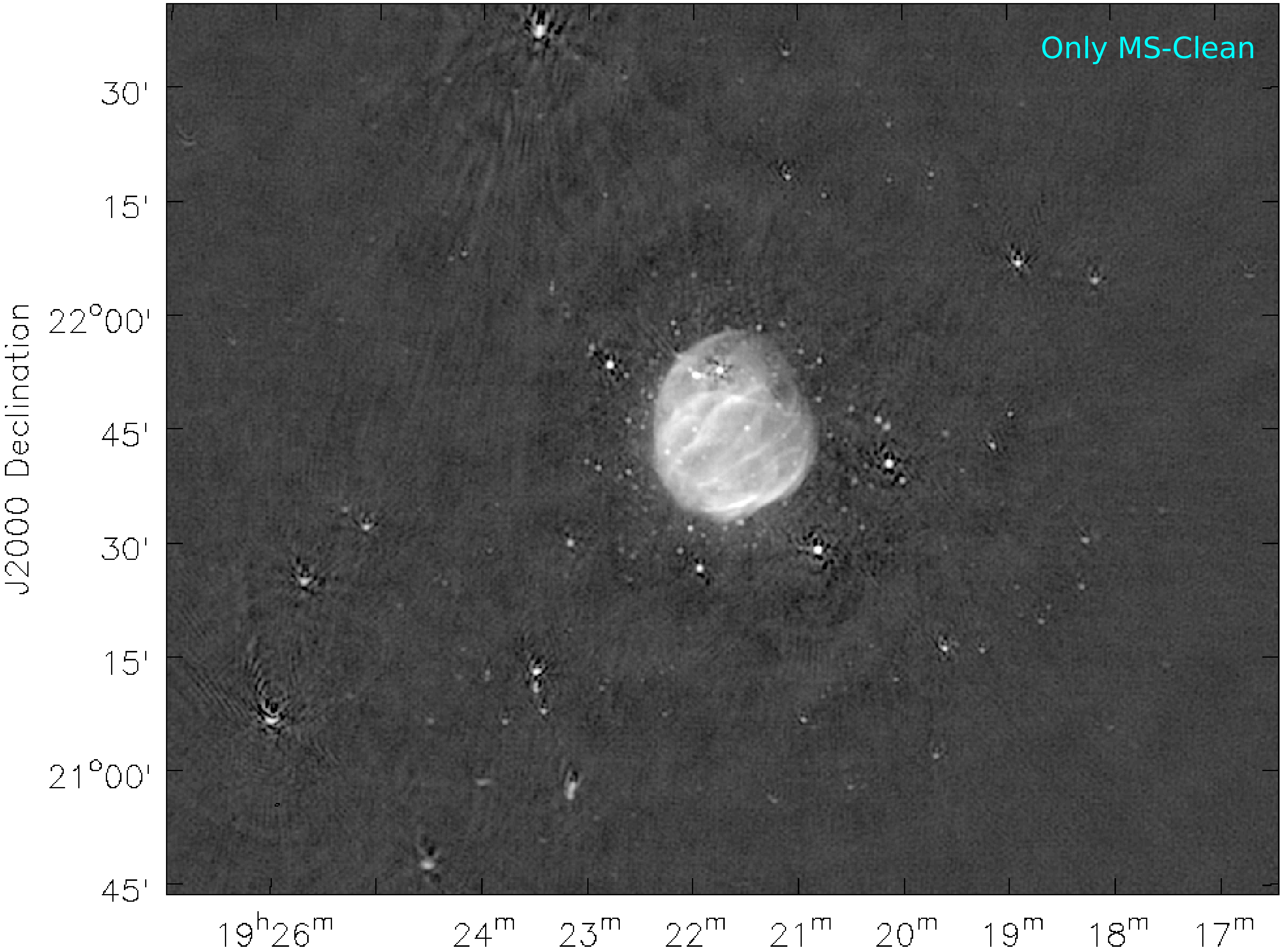
+ Single Dish

Example : Imaging the G55 supernova remnant

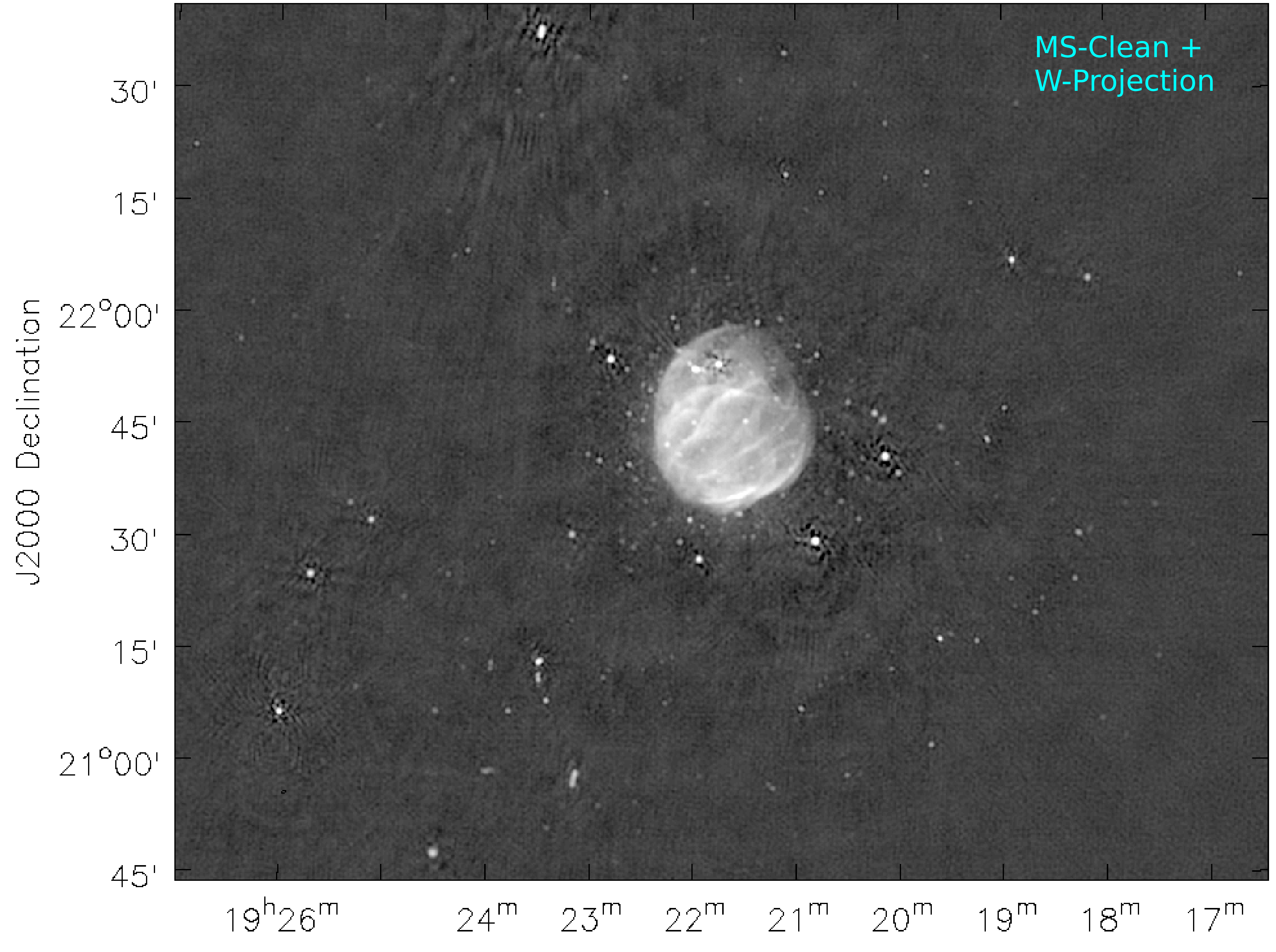
Imaging Framework

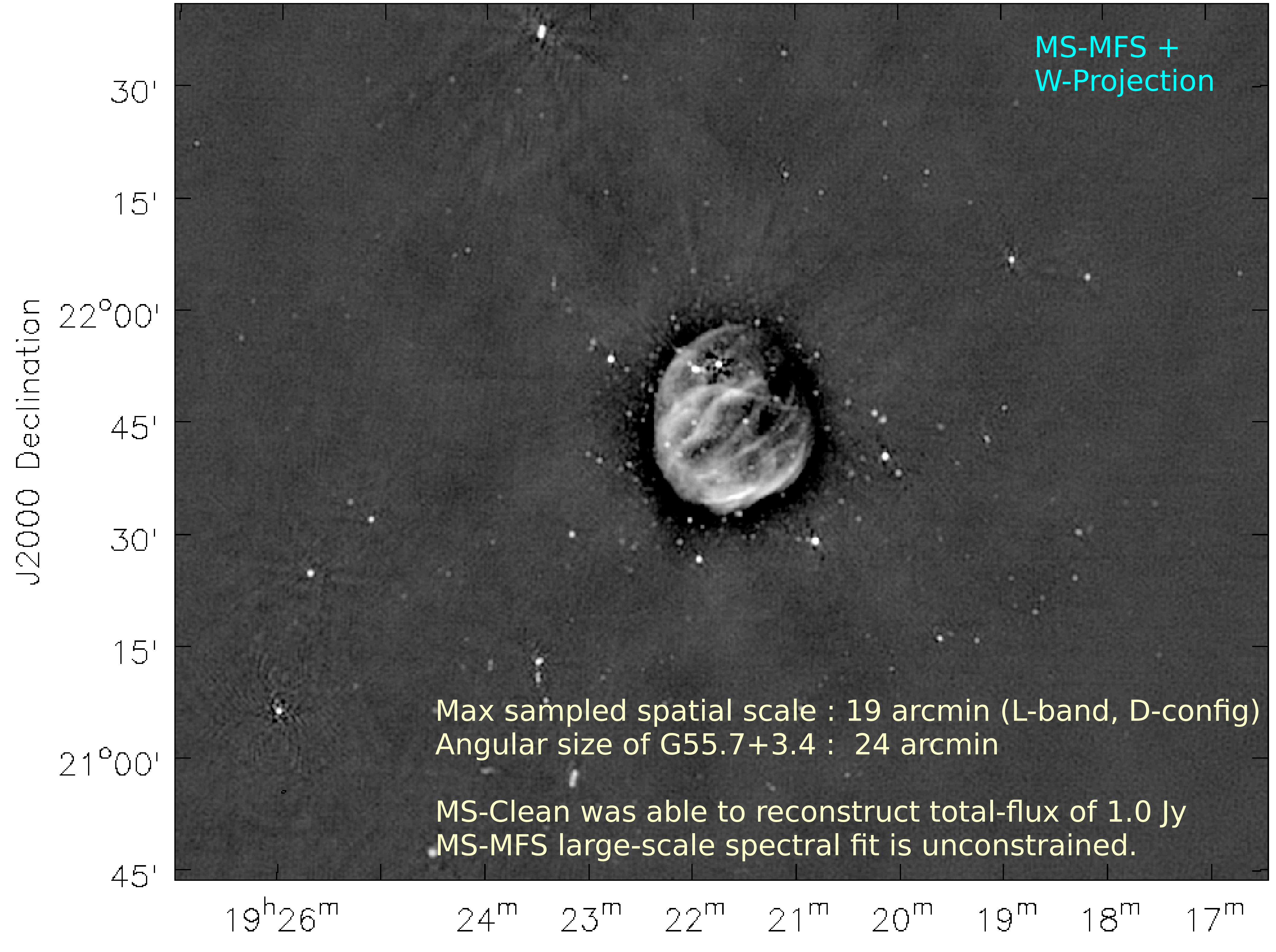


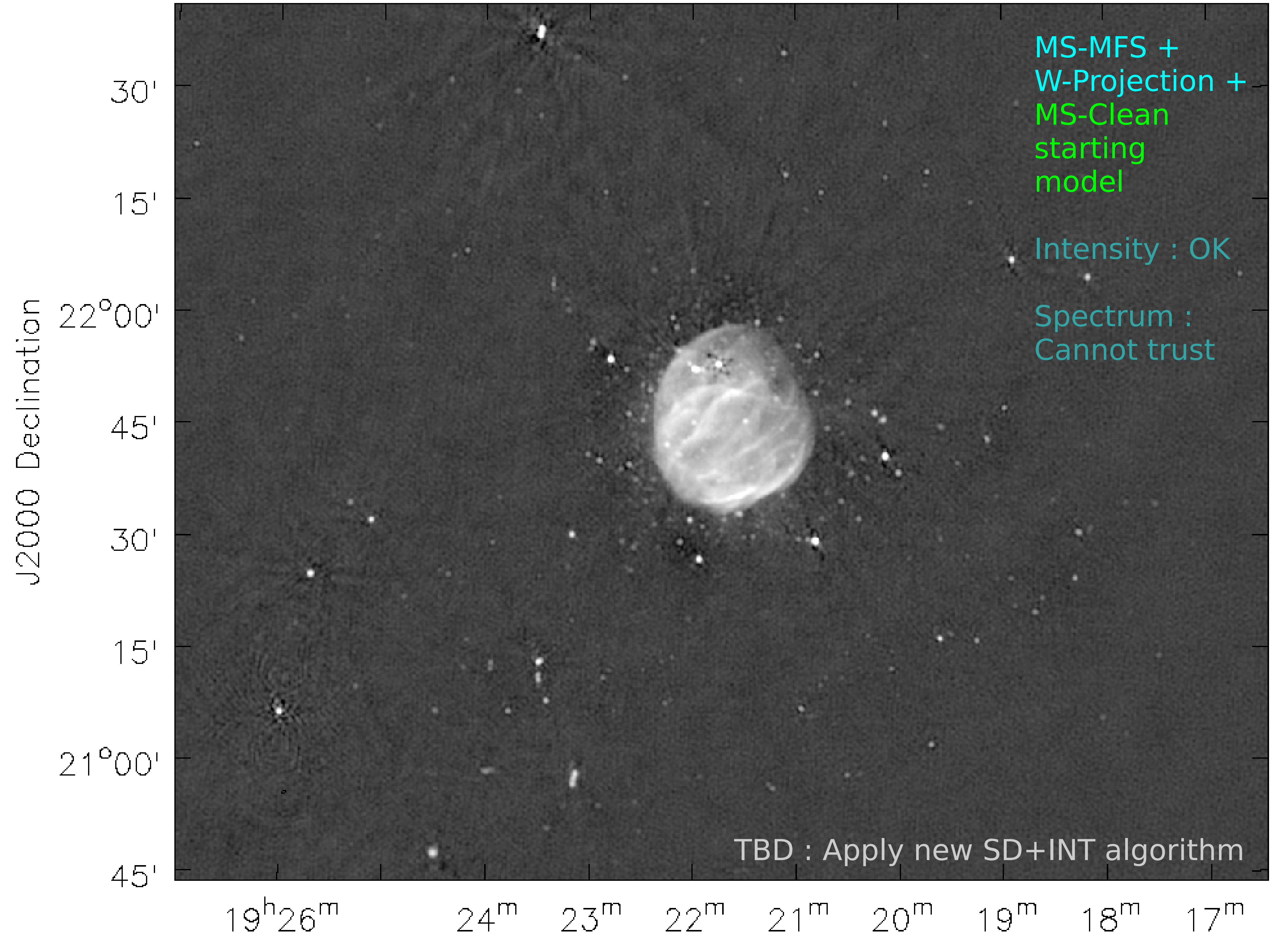
Example : SNR G55.7+3.4
7 hour synthesis, L-Band, 8 spws x 64 chans x 2 MHz, 1sec integrations
Due to RFI, only 4 SPWs were initially imaged (1256, 1384, 1648, 1776 MHz)
Imaging Algorithms applied : MS-MFS with AW-Projection
(nterms=2, multiscale=[0, 6, 10, 18, 26, 40, 60, 80])
Peak Brightness : 6.8 mJy
Extended Emission : ~ 500 micro Jy
Peak residual : 65 micro Jy
Off-source RMS : 10 micro Jy (theoretical = 6 micro Jy)
J2000 Declination
30'
15'
22°00'
45'
30'
15'
21°00'
45'
19h26m
24m
23m
22m
21m
20m
19m
18m
17m



Only MS-Clean
30'
15'
22°00'
45'
30'
15'
21°00'
45'
J2000 Declination
19h26m
24m
23m
22m
21m
20m
19m
18m
17m

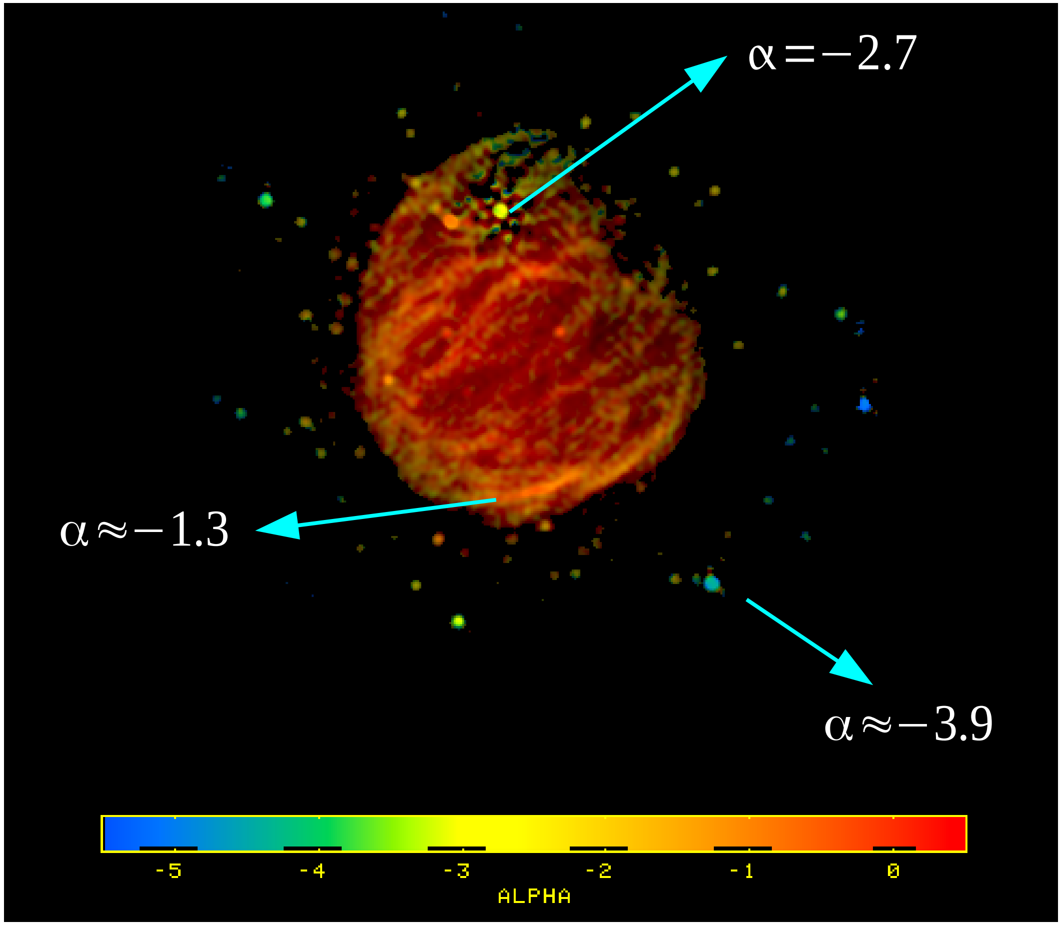

MS-Clean +
W-Projection
J2000 Declination
30'
15'
22°00'
45'
30'
15'
21°00'
45'
19h26m
24m
23m
22m
21m
20m
19m
18m
17m


MS-MFS +
W-Projection
30'
15'
22°00'
45'
30'
15'
21°00'
45'
J2000 Declination
19h26m
24m
23m
22m
21m
20m
19m
18m
17m
Max sampled spatial scale : 19 arcmin (L-band, D-config)
Angular size of G55.7+3.4 : 24 arcmin
MS-Clean was able to reconstruct total-flux of 1.0 Jy
MS-MFS large-scale spectral fit is unconstrained.

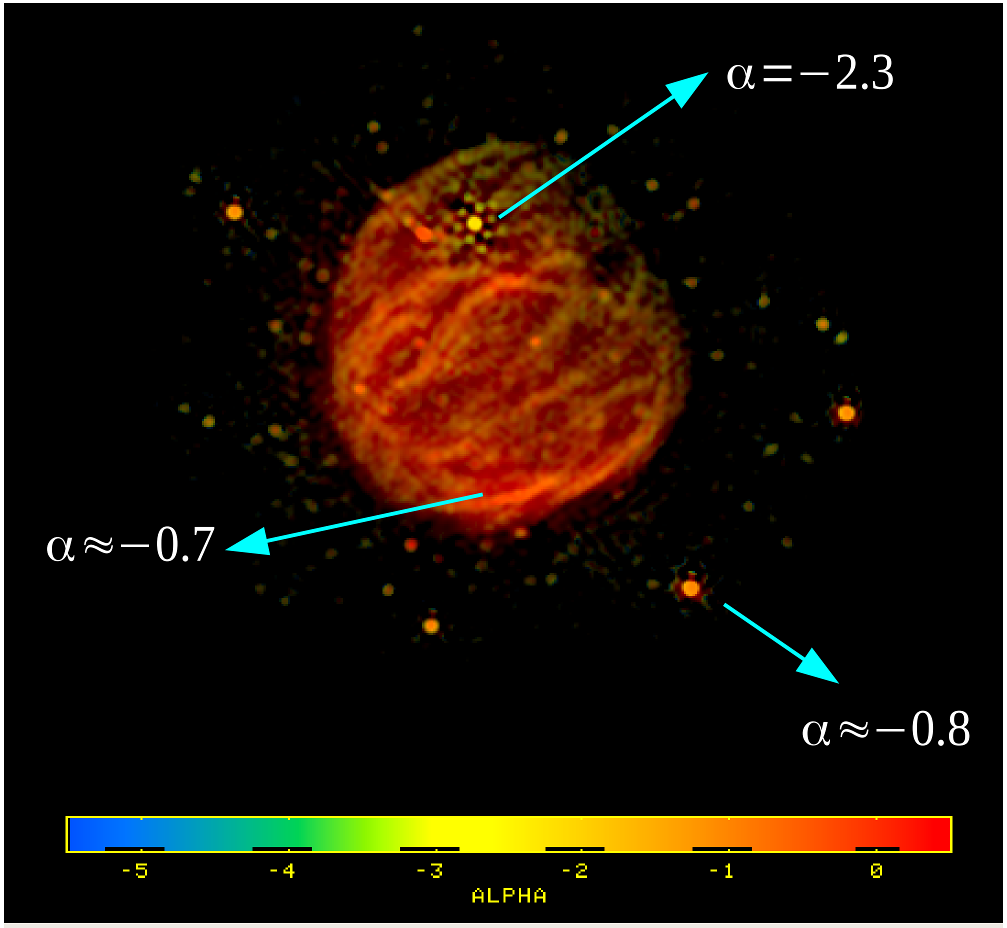

MS-MFS +
W-Projection +
MS-Clean
starting
model
Intensity : OK
Spectrum :
Cannot trust
TBD : Apply new SD+INT algorithm
J2000 Declination
30'
15'
22°00'
45'
30'
15'
21°00'
45'
19h26m
24m
23m
22m
21m
20m
19m
18m
17m

Spectral Indices before and after WB-A-Projection

Without PB correction
Outer sources are artificially steep



With PB correction (via WB-AWP)
Outer sources have correct spectra



Intensity-weighted spectral index maps (color = spectral index from -5.0 to +0.2)

Wide-field sensitivity because of wide-bandwidths

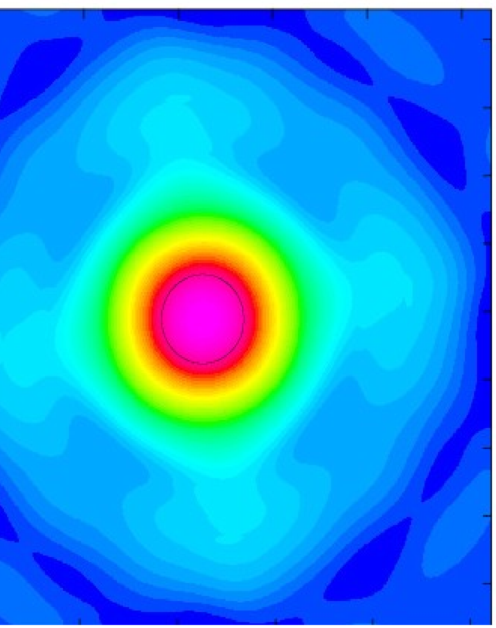
G55.7+3.4 : Field-of-view of 4x4 degrees from one EVLA pointing at 1-2 GHz

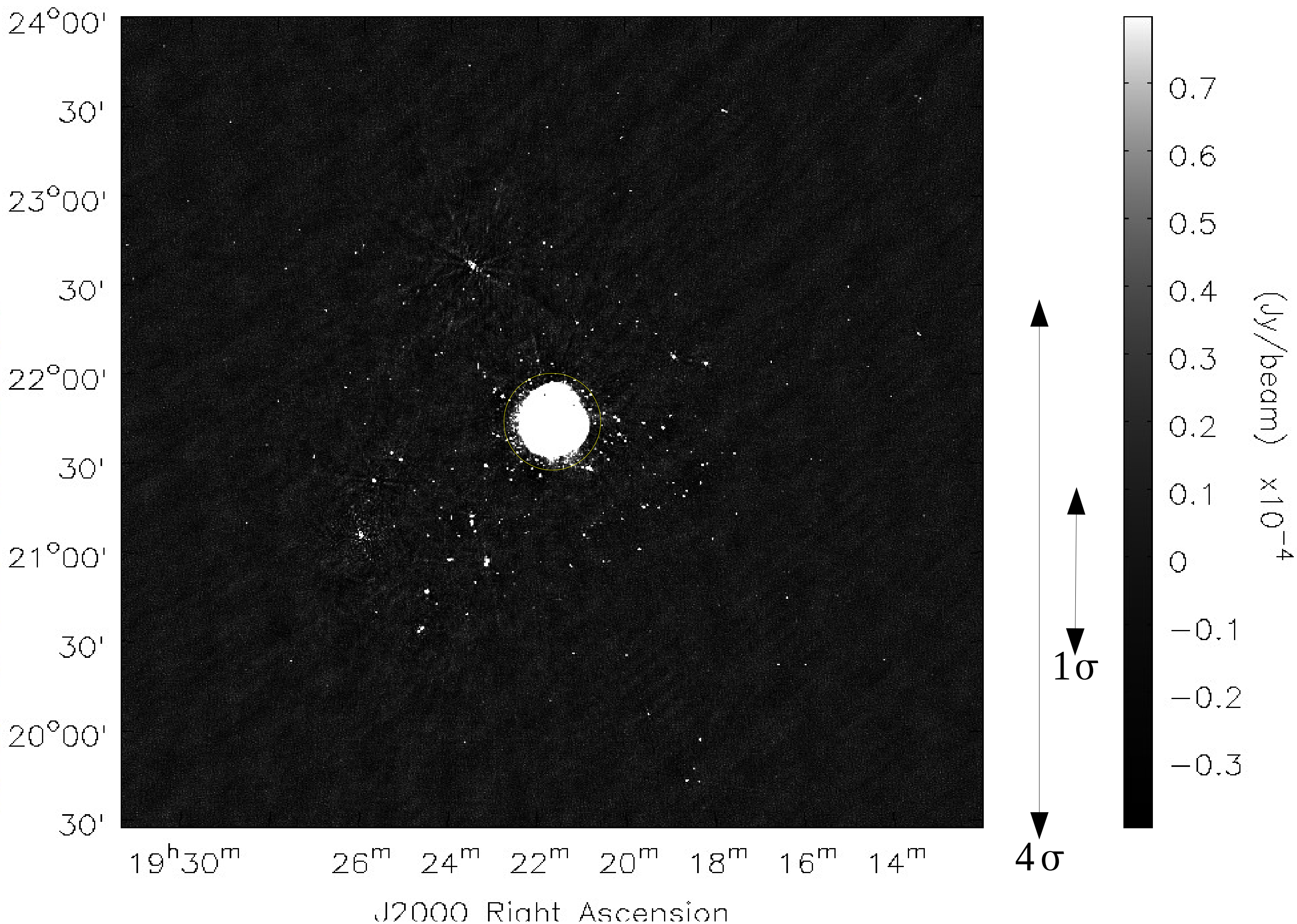
1 Jy total flux

24 arcmin

(PB: 30 arcmin)

10 micro Jy RMS





=> Wideband Imaging implies wide-field imaging

Wide Band + Full Beam/Wide-field

+ Mosaics

+ Single Dish

Example : Imaging the G55 supernova remnant

Imaging Framework

Imaging Framework - Major and Minor cycles

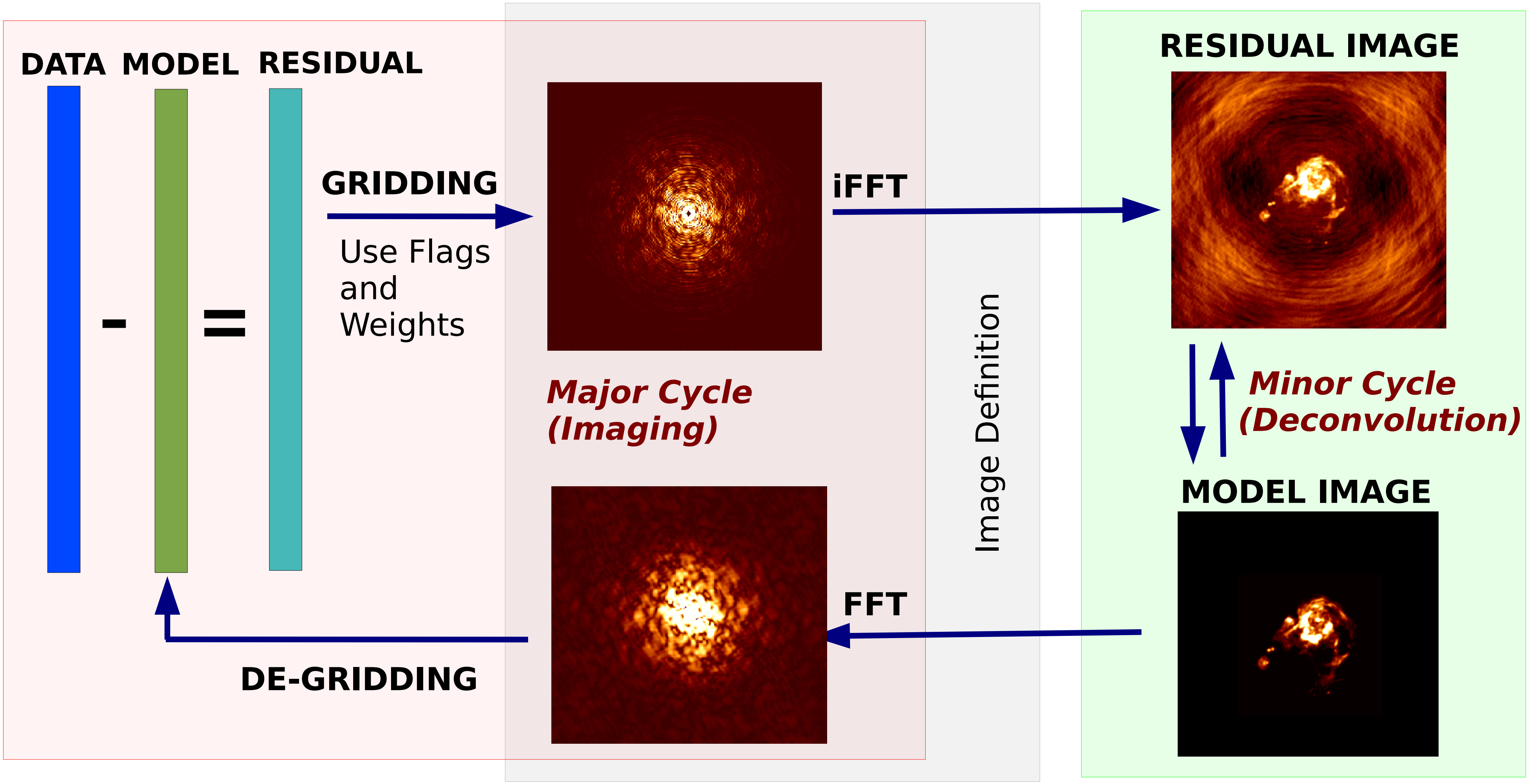
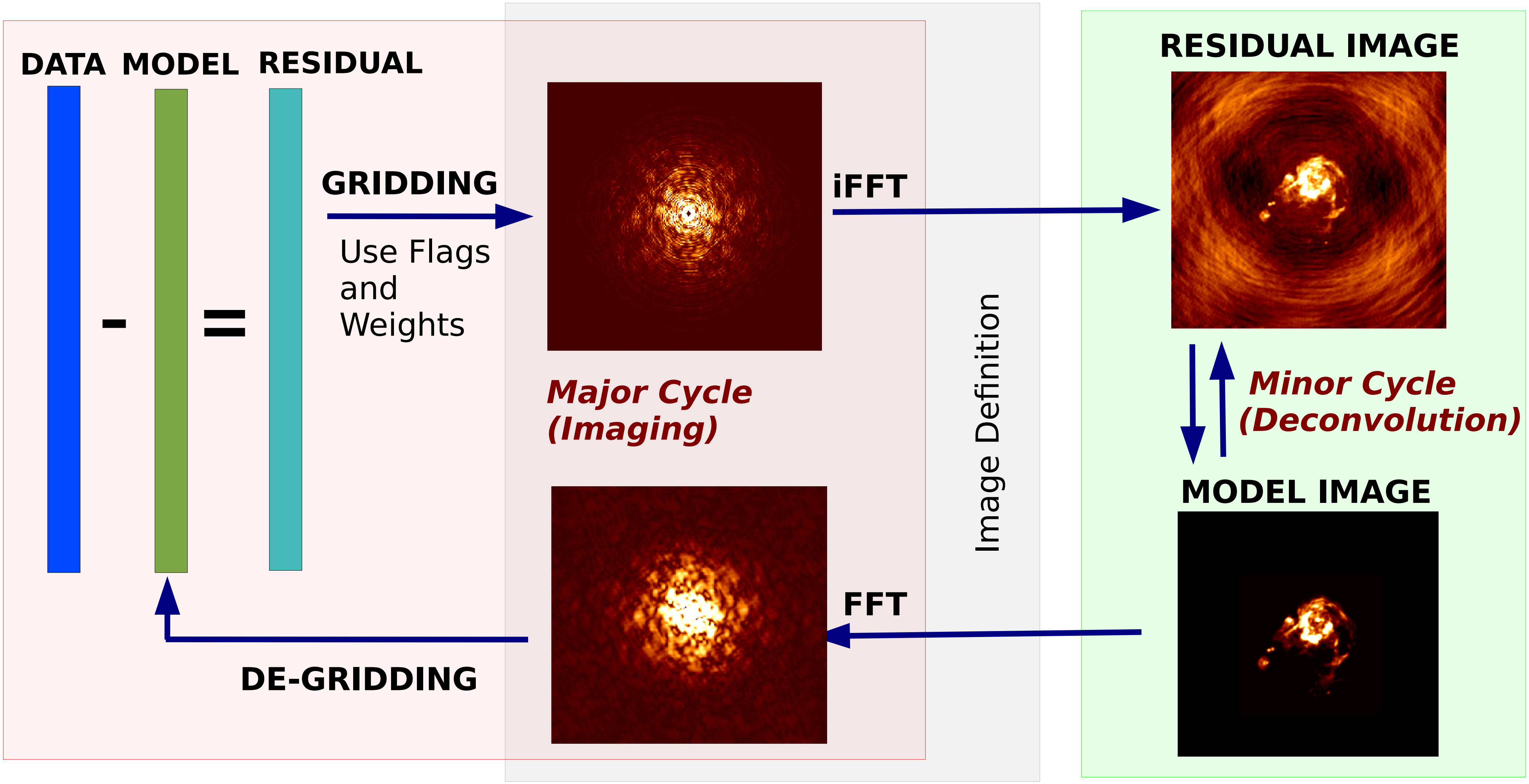


Image reconstruction is an iterative model-fitting / optimization problem

Measurement Eqn : $[A] I^m = V^{obs}$

Iterative solution : $I^m_{i+1} = I^m_i + g[A^T W A]^+ \left(A^T W \left(V^{obs} - A I^m_i\right)\right)$

Imaging & Deconvolution

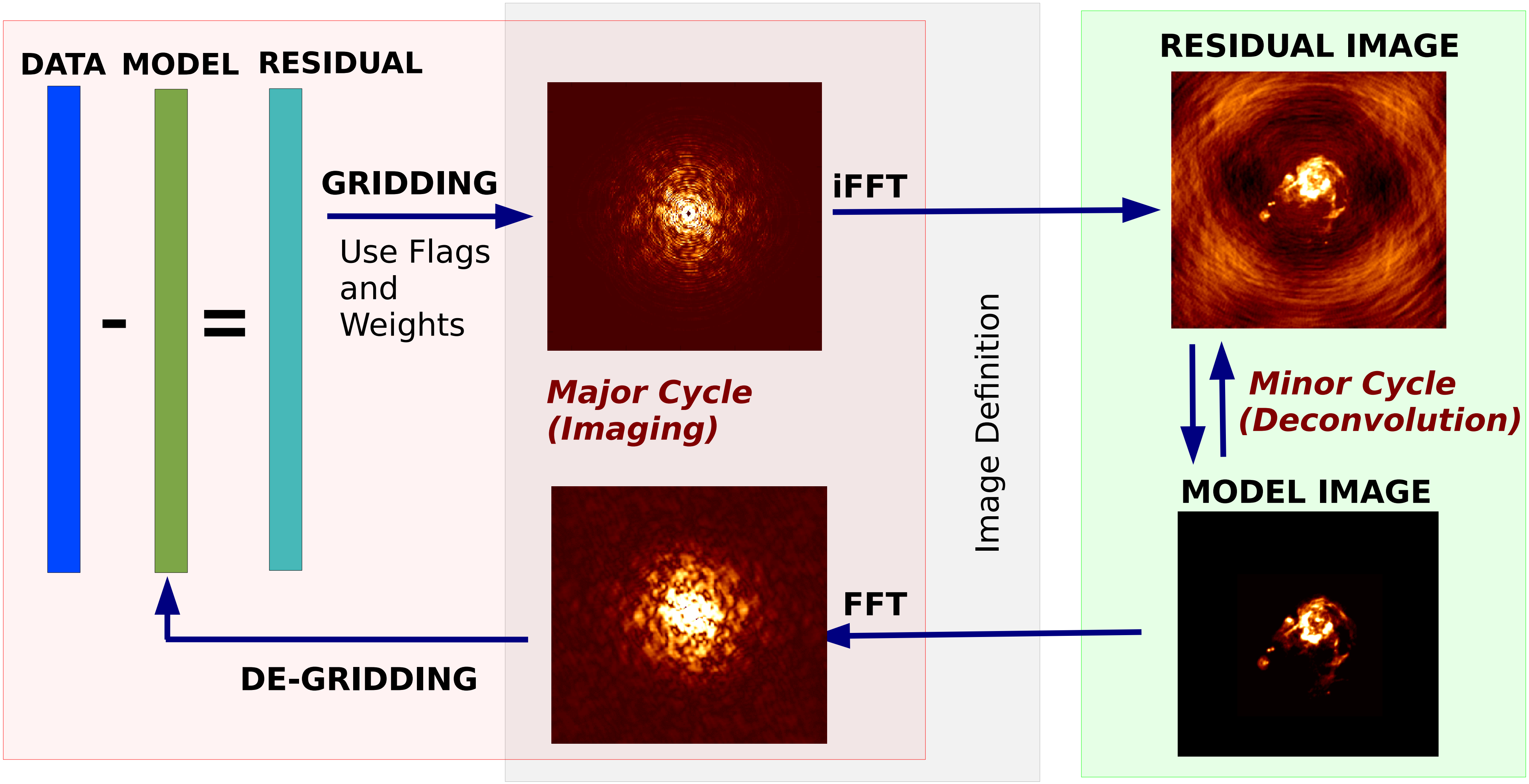


Instrumental Corrections (applied per visibility during gridding)

Mapping of data to Image Shape/Type

Solving for the sky model (non-linear optimization)

Algorithm Options

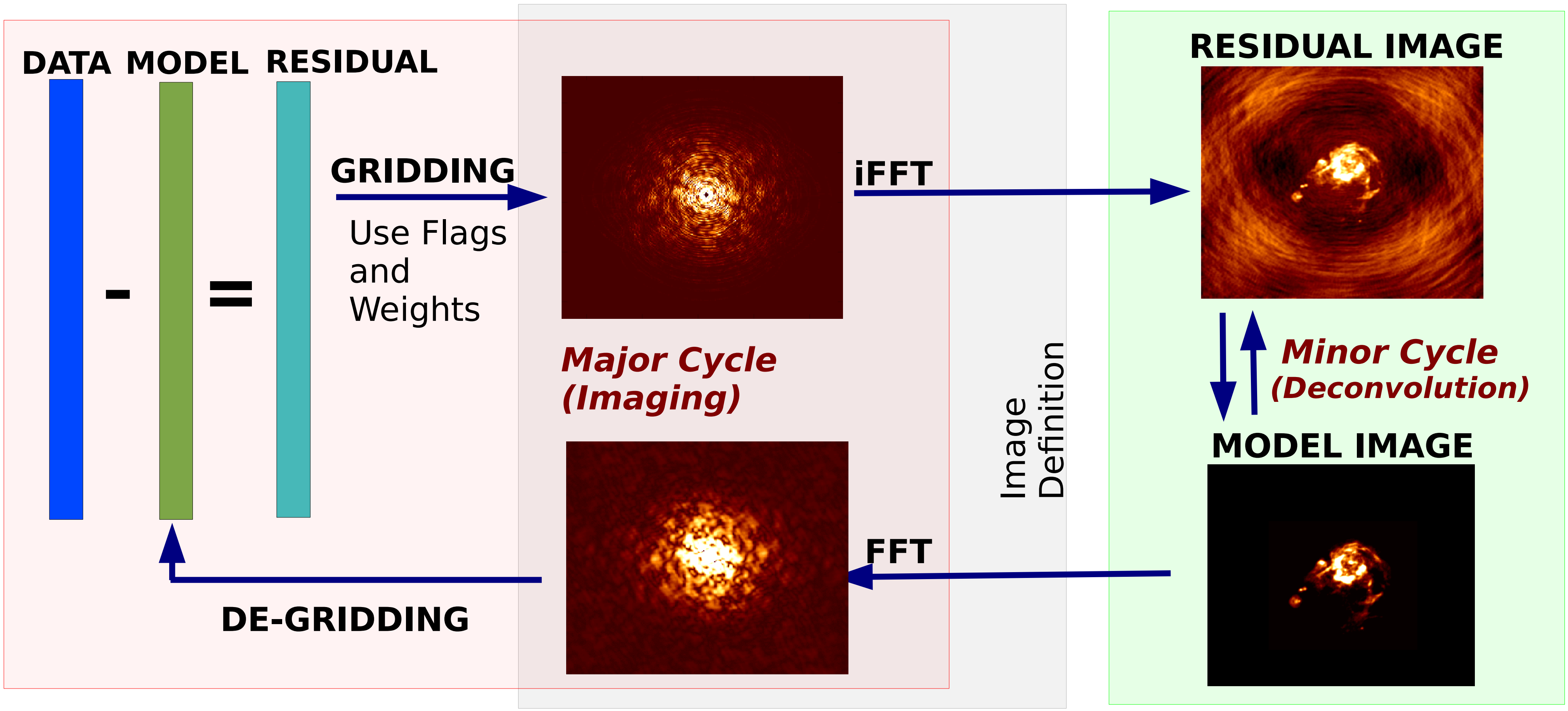


Standard gridding, W-Proj (WB)-A-Proj, Joint Mosaics, (Parallelization)

Cube, MFS, MT-MFS, Faceting,Stokes, Multi-Field, SD+INT Stitched Mosaic

Clean (Hogbom, Clark, MultiScale, MultiTerm, etc...)

Computational Cost



Runtime and computing resources depend on many factors.

=> Choose algorithms wisely....

(a) Data Volume, (b) Gridding Algorithm, (c) Joint vs Separate reconstructions, (d) Deconvolution algorithm, (e) Sky brightness structure and convergence rate (f) Dynamic range, calibration accuracy (g) Iteration Control

Summary – Lectures 1 & II

Wide Band Imaging

Sky and instrument change with frequency

=> Cube vs MFS, wideband/multiscale model, spectral index

Wide Field Imaging

non-coplanar baselines and the W-term

=> W-Projection, W-Stacking, Faceting, 3D FFTs

Full Beam Imaging

antenna primary beams

=> pbcor, A-Projection, beam models

Wide-Band + Primary-Beams + Mosaics + W-term + Single-Dish

(+ Full-Stokes Imaging + Clean/MS-Clean/etc...)

Imaging Framework

=> Flexible imaging framework implemented in software (CASA)